(212)



# Cours/Lecture Series

## 1988-1989 ACADEMIC TRAINING PROGRAMME

SPEAKER : M. JACOB / CERN-TH

TITLE : Introduction to particle physics for non particle physicists

DATES : 14, 15, 16 & 17 February

TIME : 11.00 to 12.00 hrs

PLACE : Auditorium




### ABSTRACT

*This introduction to particle physics will consist of three parts.*

*The first will be a general introduction to particle physics as it is today, its recent achievements and the questions under study, facts and hopes.*

*The second will be a review of particle physics as it developed over the past forty years. How we gradually understood the weak interactions, the strong interactions and the inner structure of the proton.*

*The third part will cover the connections between particle physics and cosmology.*


Lecture Notes Distribution : - internal (CERN) distribution only to Participants

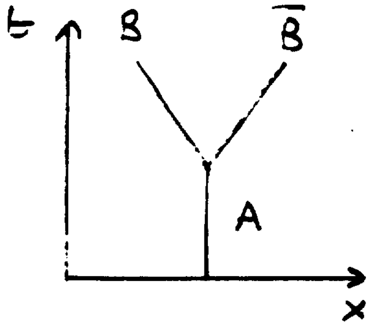
- self-service (50 copies) at CERN Main Library

- No extra copies available
- Reference copy at Main Library

# Description of an interaction

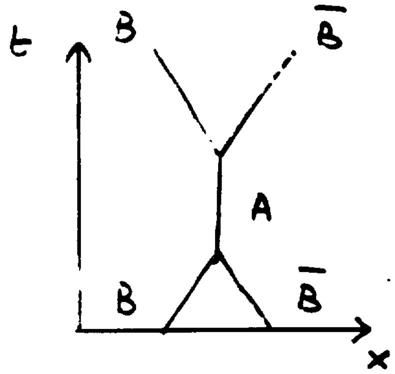
What happens to the fields as a function of time

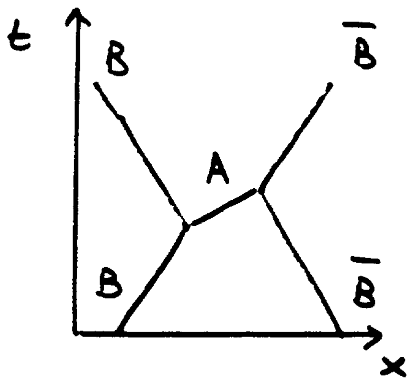
Consider all possible histories

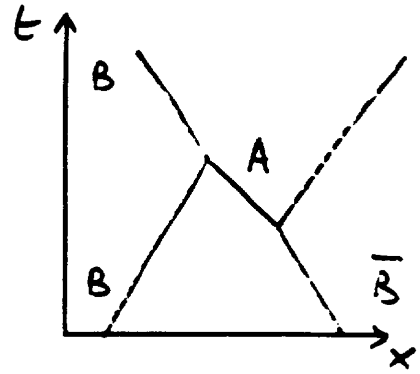



A decays into $B\bar{B}$

$B\bar{B}$ scattering



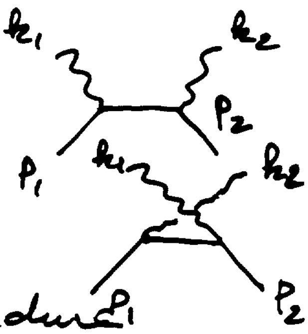

$B\bar{B}$ annihilate

B emits
$\bar{B}$ absorbs

$\bar{B}$ emits
B absorbs

Sum over all histories, since all occur,
and with a relativistic view of space and time

→ Feynman Graphs

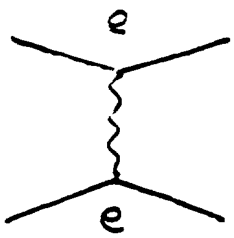



Specifies only momenta and topology
and not positions in space and time

Picture Guide for specific calculation procedure

# QED Quantum Electrodynamics

$g-2$

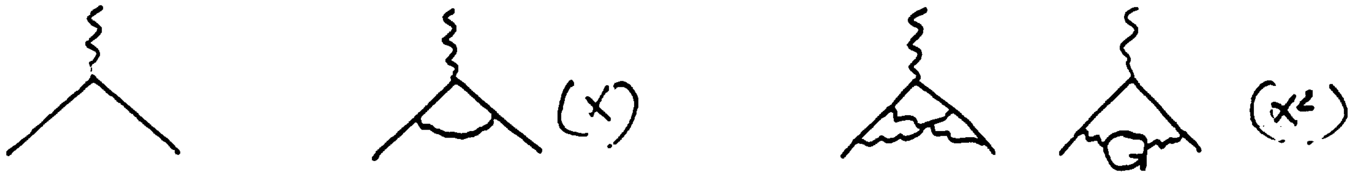



Simplest process in electron-electron scattering

$e^2$ $\quad \alpha = \dfrac{e^2}{\hbar c} = \dfrac{1}{137}$

Contribution to order $\alpha$

The anomalous moment of the muon $(g-2)$




$\mu = g \frac{e}{2m} s \qquad s = \frac{\hbar}{2}$ $\qquad + \cdots$

$g = 2 \qquad g = 2\left(1 + \frac{\alpha}{2\pi}\right)$

$a = \frac{1}{2}(g-2)$

All terms of different topology and the same number of vertices.

Present calculated value $a = 0.001165921$ (8.8)

Present measured value $a = 0.001165924$ (8.5)

| Theory | | | Experiment | |
|---|---|---|---|---|
| 48 | 2 | $10^{-3}$ | | |
| 50 | 4 | $10^{-6}$ | 61 | 0.001145 (22) |
| 71 | 6 | $10^{-8}$ | 72 | 0.0011616 (31) |
| 77 | 8 | $10^{-9}$ | 79 | 0.001165924 (8.5) |

The highest precision in physics

# The Weak Interactions

Neutron β decay

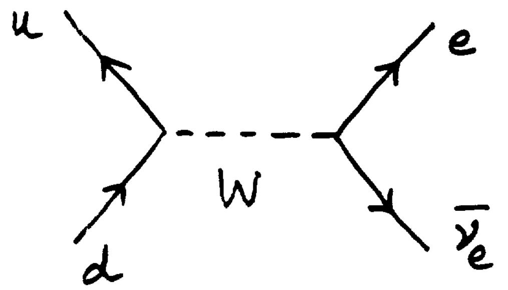
$n \rightarrow p + e^- + \bar{\nu}$ (~ 100 sec)

0.940 0.938 0.0005

$d \rightarrow u + e^- + \bar{\nu}$

(udd) (uud)

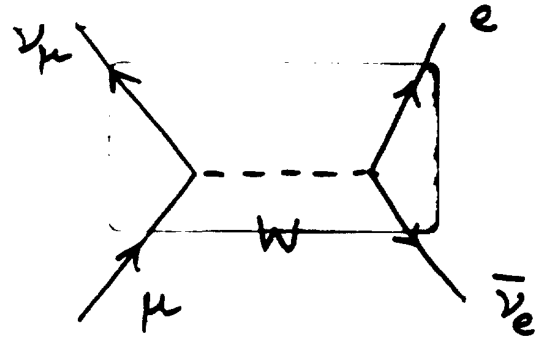
Influence of Nuclear environment




Transition through a very massive virtual state

$M_W = 81$ GeV

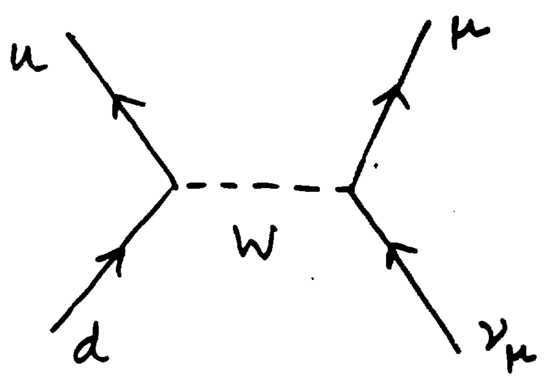
Very short time → Small probability
→ Short range




$m_\mu \sim 105$ MeV

$\tau \sim 10^{-6}$ sec

$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

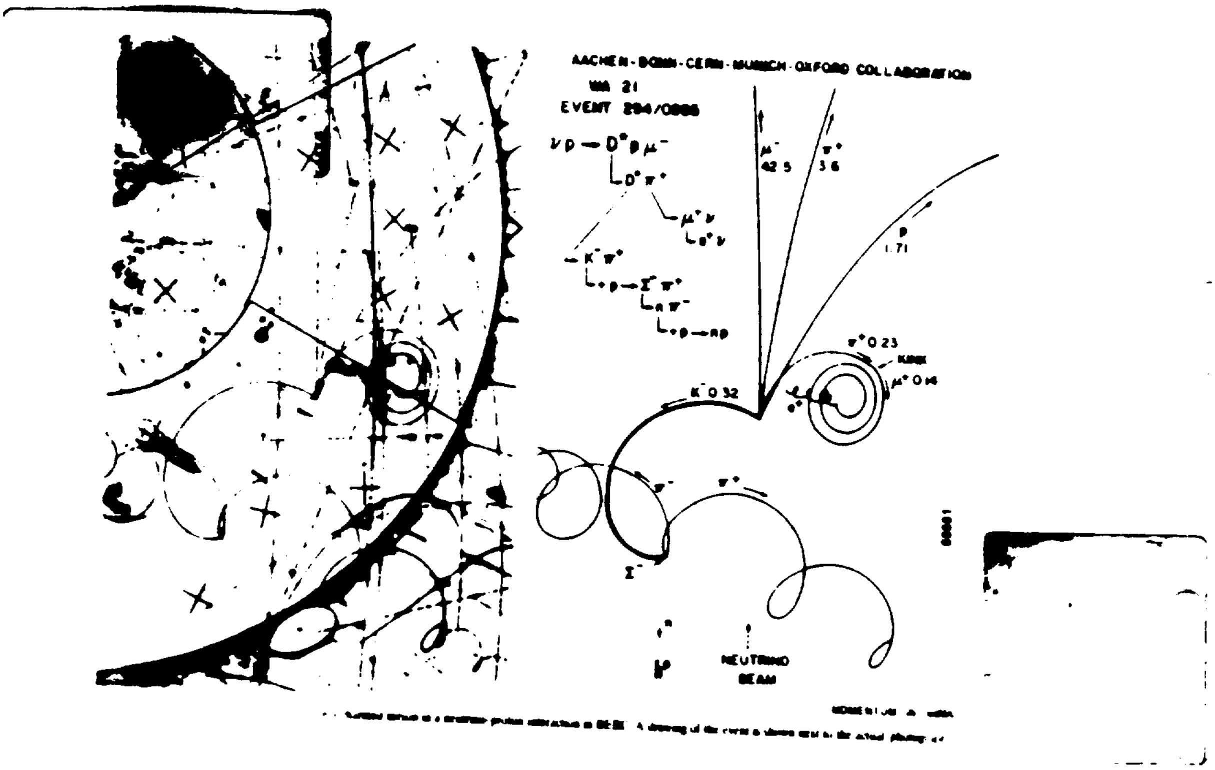



neutrino reaction

Change outgoing antiparticle into ingoing particle

$\nu_\mu + d \rightarrow \mu^- + u$

(n) (p)




$\nu p \rightarrow D^{*} p \mu^{-}$

$\nu \rightarrow \mu$

$d \rightarrow c \rightarrow (c\bar{d})$

$d$

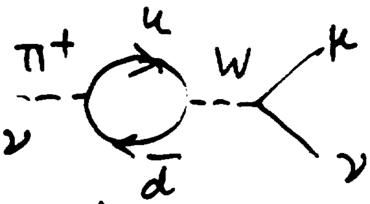
$\downarrow$

$D^{0}\pi^{+}$

$c \rightarrow s$

$D^{0} \rightarrow K^{-}\pi^{+}$

$\pi^{+} \rightarrow \mu^{+}\nu$




$\mu^{+}\nu \rightarrow e^{+}\nu\bar{\nu}$

$\mu^{+} \rightarrow \bar{\nu}_{\mu}$

$K^{-}p \rightarrow \Sigma^{-}\pi^{+}$

$\Sigma^{-} \rightarrow n\pi^{-}$ $\quad s \rightarrow u$

Charm production and decay in BEBC

A Choregraphy of Weak processes all reducible to a unique mechanism.

$$\sigma_\nu \sim 10^{-38}\ \text{cm}^2\ E_\nu\ (\text{GeV})$$

$$\sigma_p \sim 10^{-26}\ \text{cm}^2$$

Very small probability of interaction

Increasing with energy (No short time constraint)

The weak interactions remain weak as long as the energy is small with respect to the W mass

Virtual process!

Would become large at high energy
Signals more serious problem
Lack of renormalisability

Needs cancellations → more symmetry

Gauge theory — Weak and Electromagnetic Interactions

Glashow Weinberg - Salam

't Hooft

Neutral Currents

$W^+$ $W^-$ $Z^0$ $\gamma$

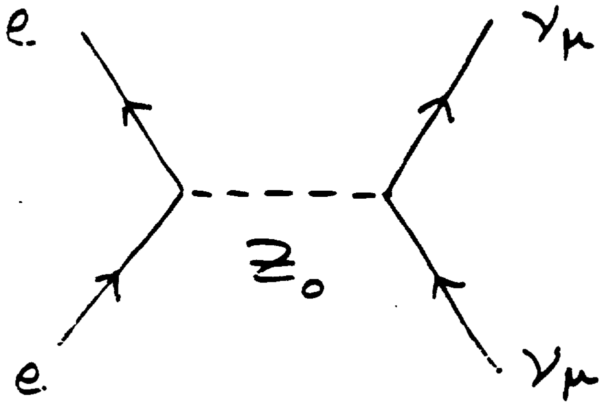
81 GeV 92 GeV Masses

Symmetry breaking Higgs Mechanism

at least one extra scalar particle (mass?)

# The ElectroWeak Interactions

$W^+ \quad W^- \quad Z \quad \gamma$



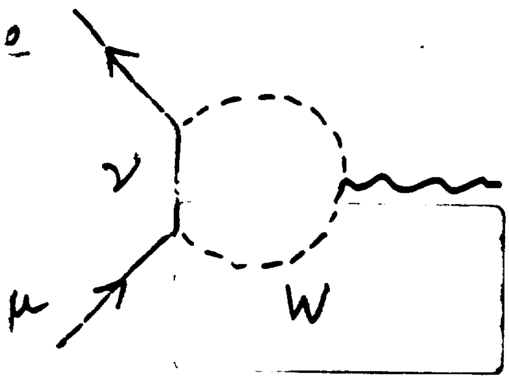

Neutral Current Interactions

1973

A. Lagarrigue
P. Musset et al

The first problem with the W (late fifties)

$\mu \not\to e\gamma$



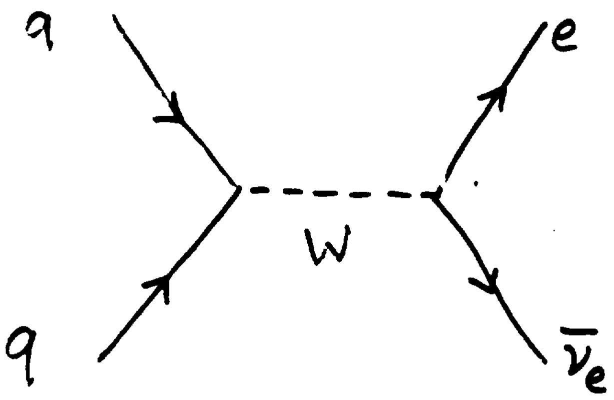

→ 2 neutrinos

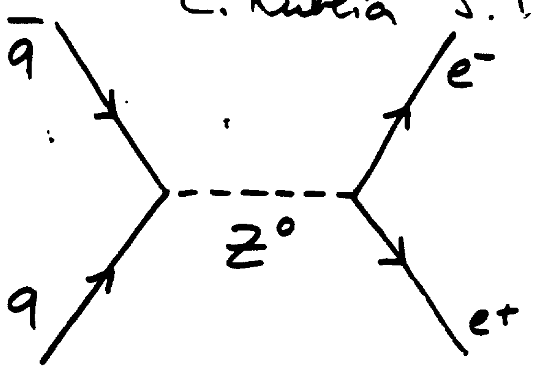
$\nu_\mu \neq \nu_e$

Lederman - Schwartz - Steinberger et al
1962

Discovery of the W and Z 1983

C. Rubbia S. Van der Meer et al



IX

# The Discovery of the Neutral Current Interaction

## Gargamelle 1973

$\nu p \rightarrow$ hadrons $+ \nu$

$\nu e \rightarrow \nu e$

the electron radiates photons which turn into $e^+e^-$ pairs

# The Electroweak theory

- A Gauge theory of Weak and Electromagnetic Interactions

$\mu \leftrightarrow \nu_\mu$ $Q = -1, 0$ R

$e_L \leftrightarrow \nu_e, \ldots$ $Q = -1, 0$ L

$d \leftrightarrow u, \ldots$ $Q = -\frac{1}{3}, \frac{2}{3}$

c

SU(2) $\left\{ W^+, W^0, W^- \right.$ doublet

U(1) $B_0$

mix $\rightarrow$ $\theta_W$ $\left\{ Z^0 \text{ (couples to } \nu\text{)}, \gamma \text{ (does not)} \right.$

Couple to $\nu$

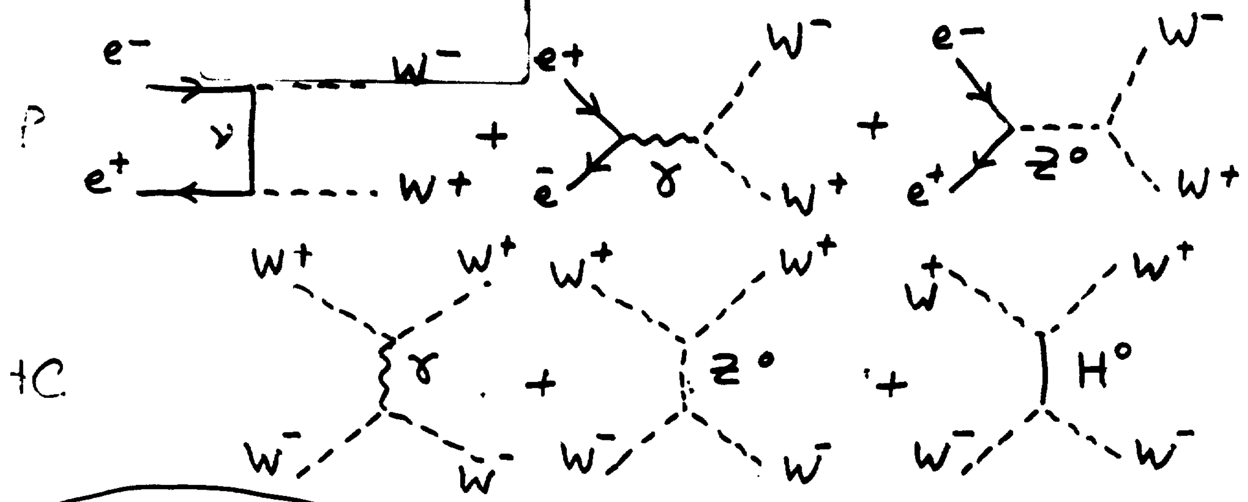
All massless but

Landau-Ginzburg

or this is a gauge version of an old trick of solid state physics. The Higgs mechanism

Vacuum Screening

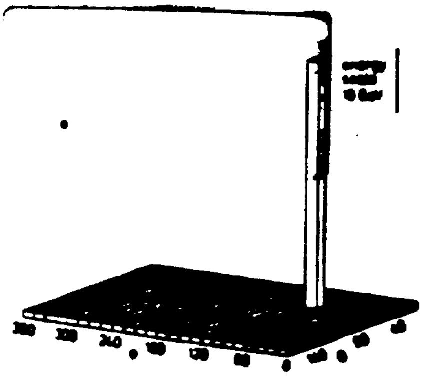
Introduce scalar fields with non zero vacuum expectation values



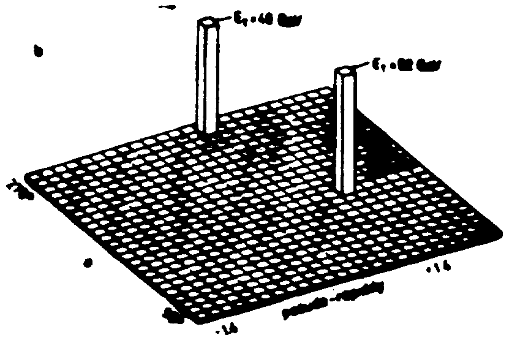

Hidden Symmetry: Enough symmetry remains:

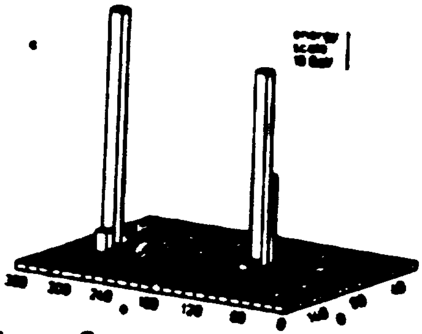
Here, at the set up rendez-vous

$W \to e\nu$



$Z \to e^+e^-$





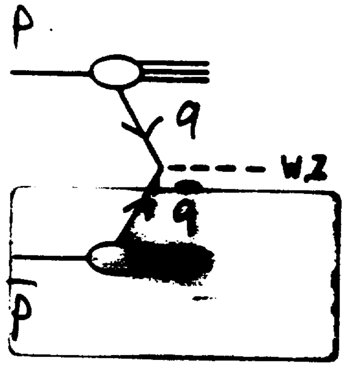
two jet event

$\sigma_{e\nu} \sim 5 \times 10^{-34}\ cm^2$

$\sigma_{e^+e^-} \sim 5 \times 10^{-35}$

$\sigma_{tot} \sim 5 \times 10^{-26}$

$(10^{-8})$




The discovery of the W and Z

UA1, UA2 1983

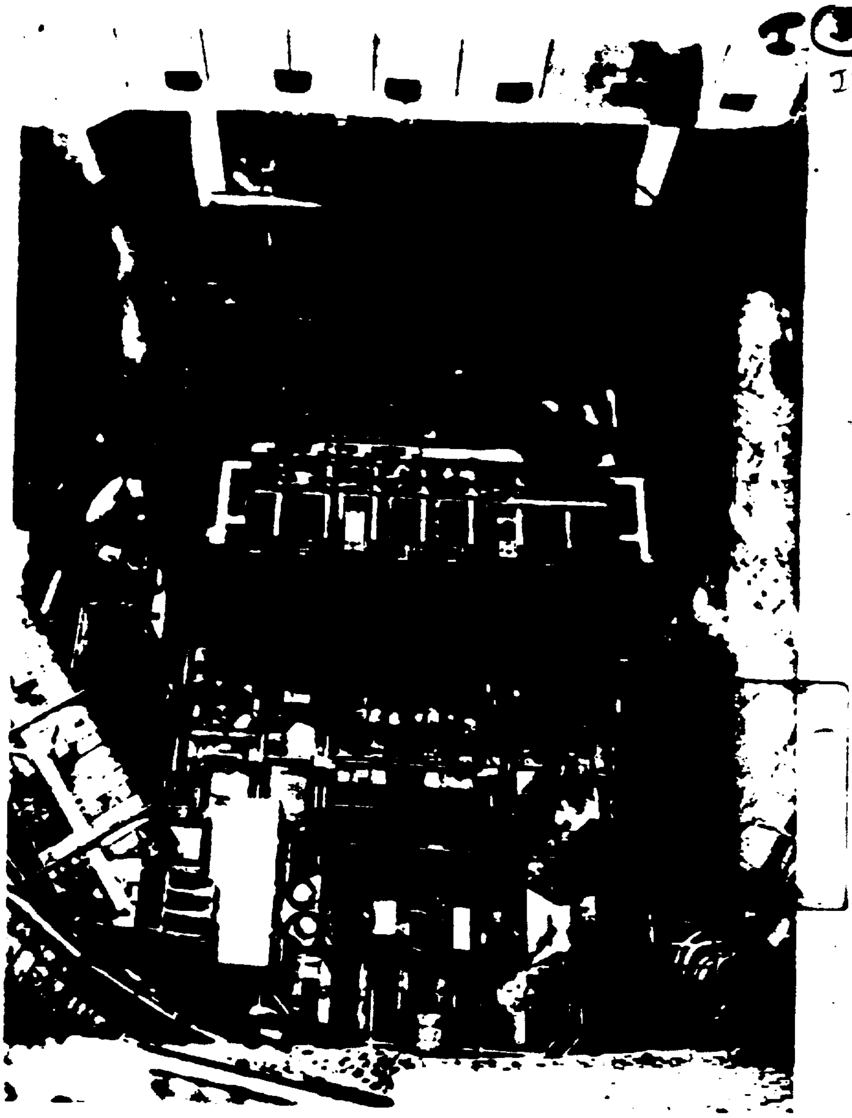
$q\bar{q} \to W \quad e\nu$

$q\bar{q} \to Z \quad e^+e^-$

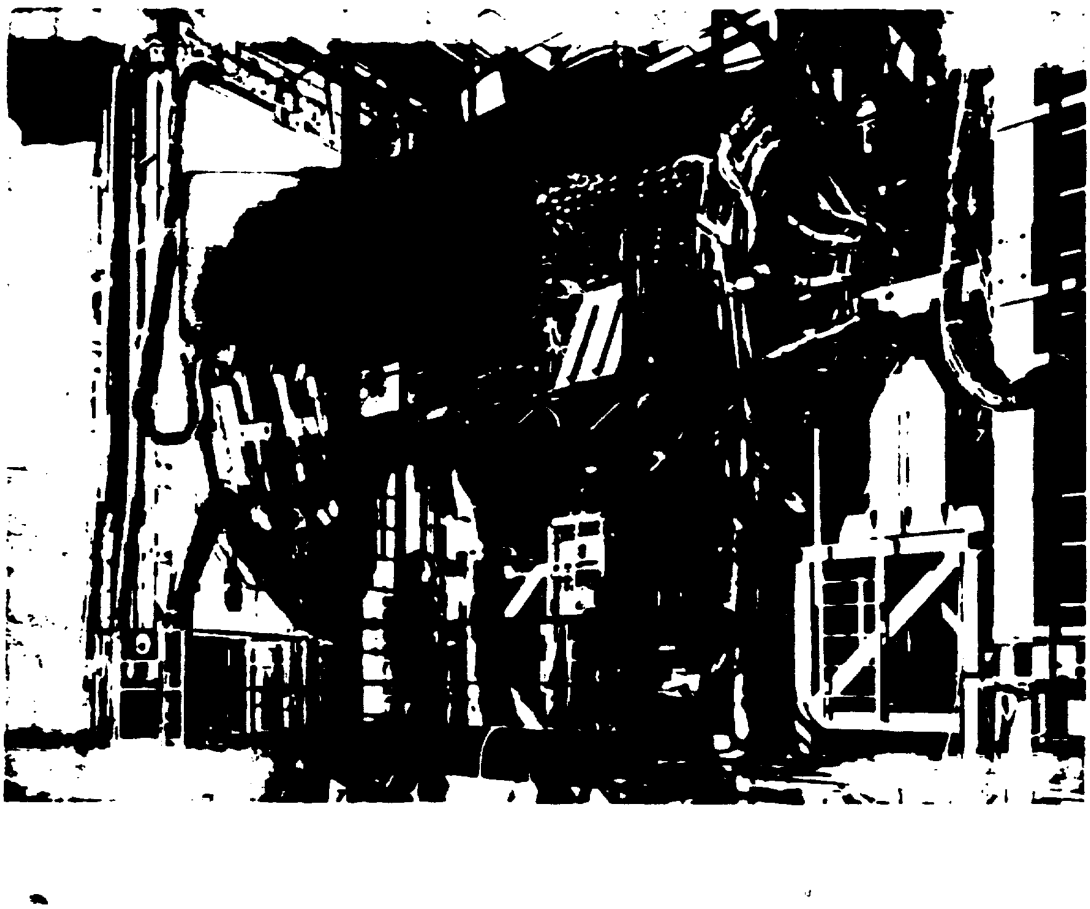
Note the clarity of the event structure

It required the transformation of the SPS into a $p\bar{p}$ Collider

The construction of highly sophisticated imposing detectors



UA1



UA2

The W raised to the rank of a Chinese character.

## 高能物理学又有新突破！

# 核子中存有W粒子

人类对核子的认识又有新的突破！

瑞士日内瓦的欧洲核子研究机构，在最近的一次实验中，证实了核子中存在有W粒子。这种W粒子的发现将有助于人类对核子做进一步的研究。

这项物理学上的新突破，最近成了世界著名科学界所瞩目的大条新闻。

欧洲核子研究机构中心理论组主任贾里斯雅各布，昨天在我国受访时透露这项消息。

他说，W粒子的产生，是利用质子和反质子在加速器中互相碰撞的结果。

他说，在过去，人类发现电力和磁力可以统一，从而发展了电子、半导体、无线电波等科技。

欧洲核子研究机构中心理论组主任贾里斯雅各布。

现在发现了W粒子，表示我们已知道如何统一辐射力和电磁力。因为在理论上，如果辐射力和电磁力取得统一，就必会产生W粒子和Z°粒子。

目前，欧洲核子研究机构已发现了W粒子，而Z°粒子则正还在实验中。据所知，W粒子的质量比质子重70倍左右。

他指出，由于做这项实验需要用到非常复杂和先进的电脑软件，因此，这使到欧洲核子研究机构成为当今欧洲最大的电脑软件研究和咨询中心。

“此外，进行这项实验所需的配备，也可以做其他方面的用途，例如发展高速电子技术和超导体电磁的制造。”

据科学界人士预测，欧洲核子研究机构的这项重大发现将会获得诺贝尔奖。

雅各布现年60岁，法国人，是法国科学学院最年轻的一位副院士。他在欧洲核子研究机构服务已有16年，专门研究粒子和核子的问题。

他此次来新，是想了解是否有可能和本地科学界在物理和电脑方面进行交换计划。

欧洲核子研究机构创办于1954年，纯粹是一个国际性的科学机构，专门研究物质的结构。目前，该机构拥有13个会员国家，英国、法国、德国、意大利、瑞士、奥地利、比利时、荷兰、丹麦、瑞典、挪威和希腊。

欧洲核子研究机构这一次的重大发现，也使到欧洲在核子研究方面足以和美国分庭抗礼。

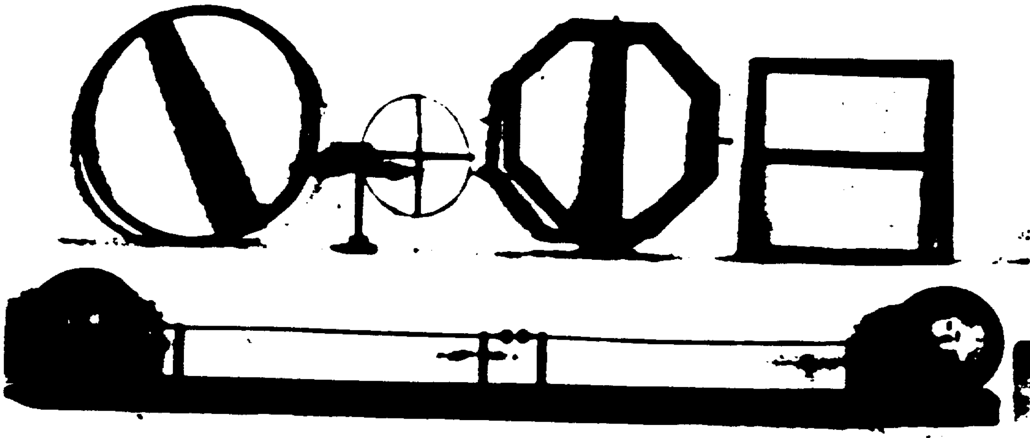
（P08PW）

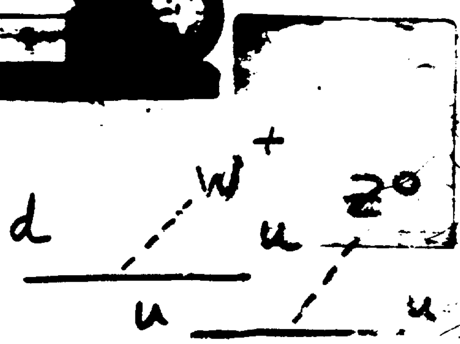
In A Singapore Newspaper, March '83

J41


1890

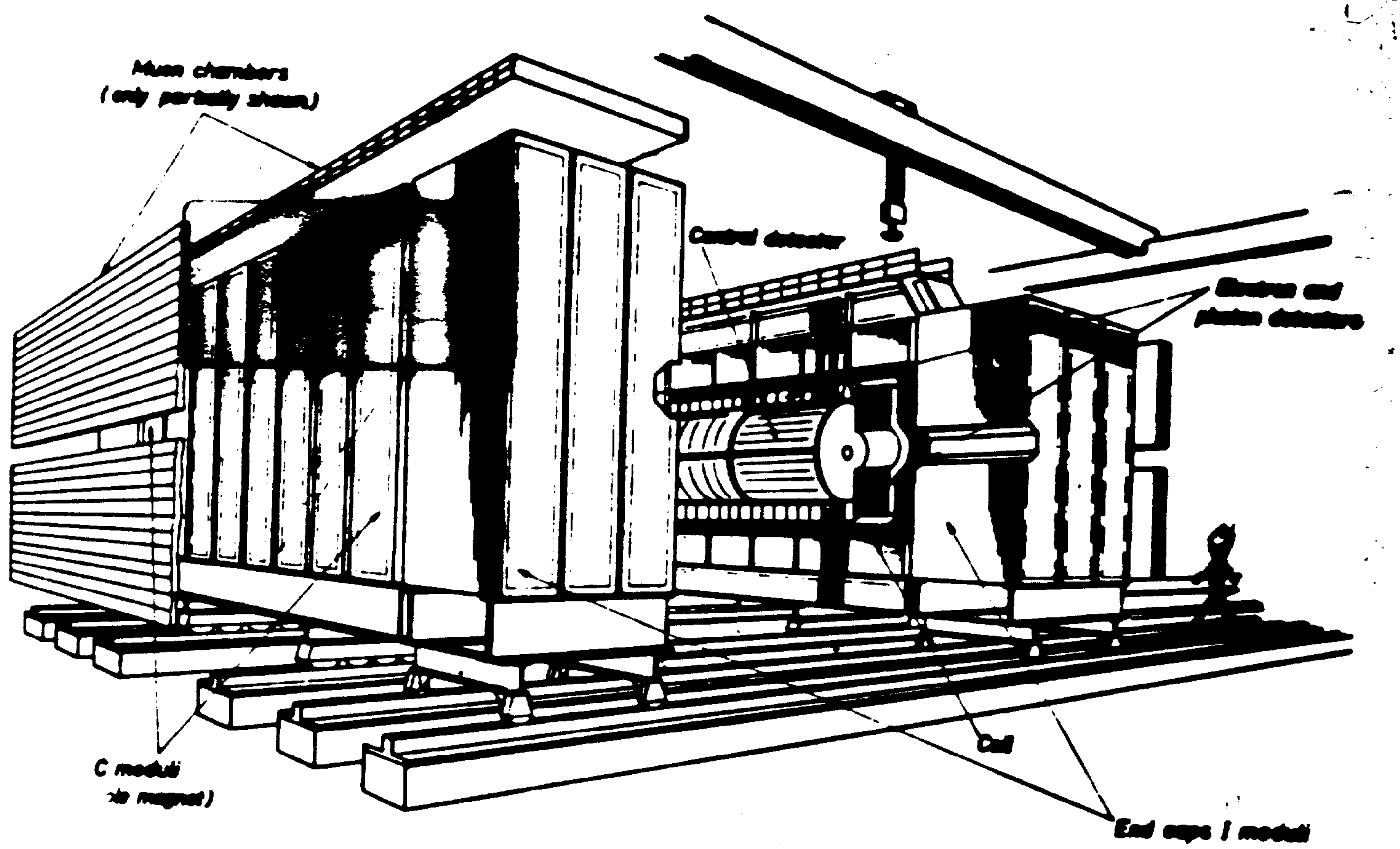
The Hertz experiment
Electromagnetic Radiation



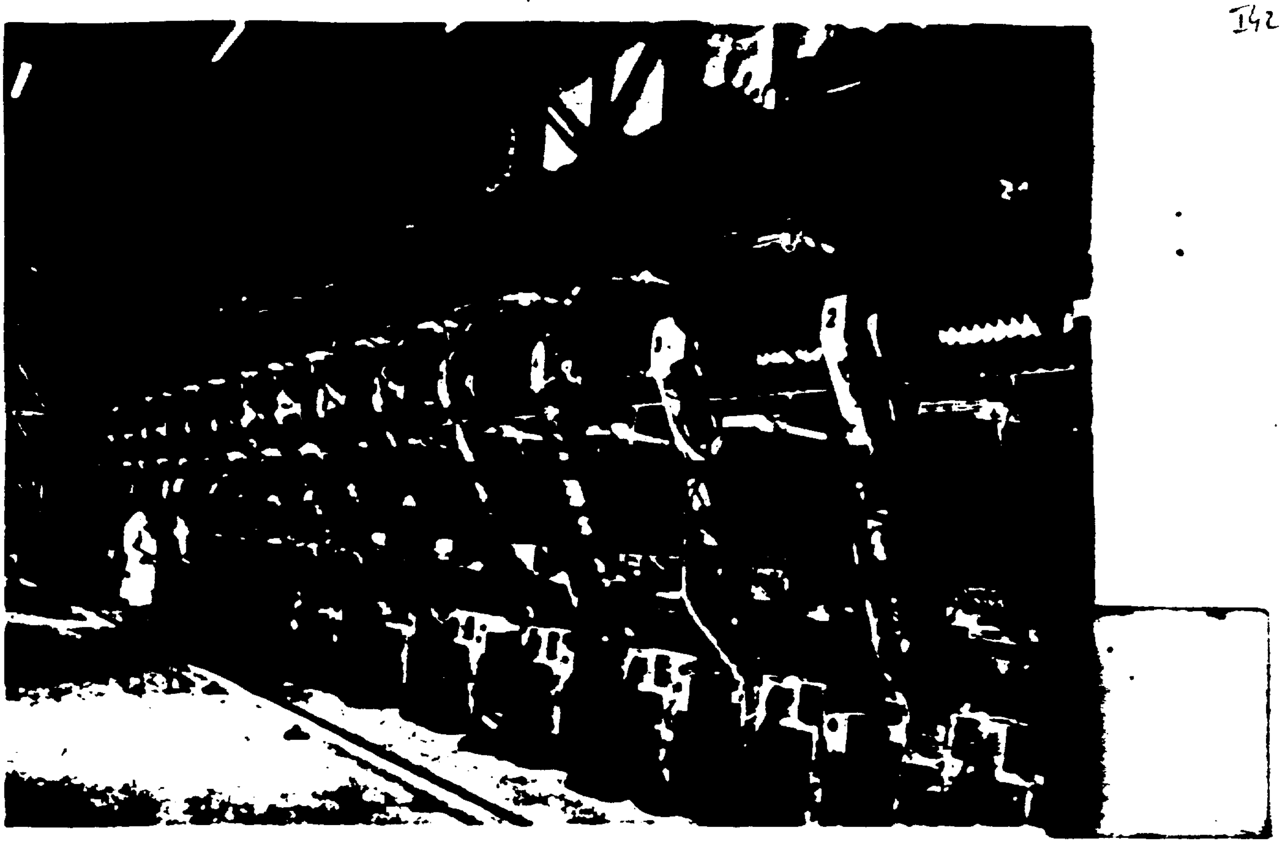



1980

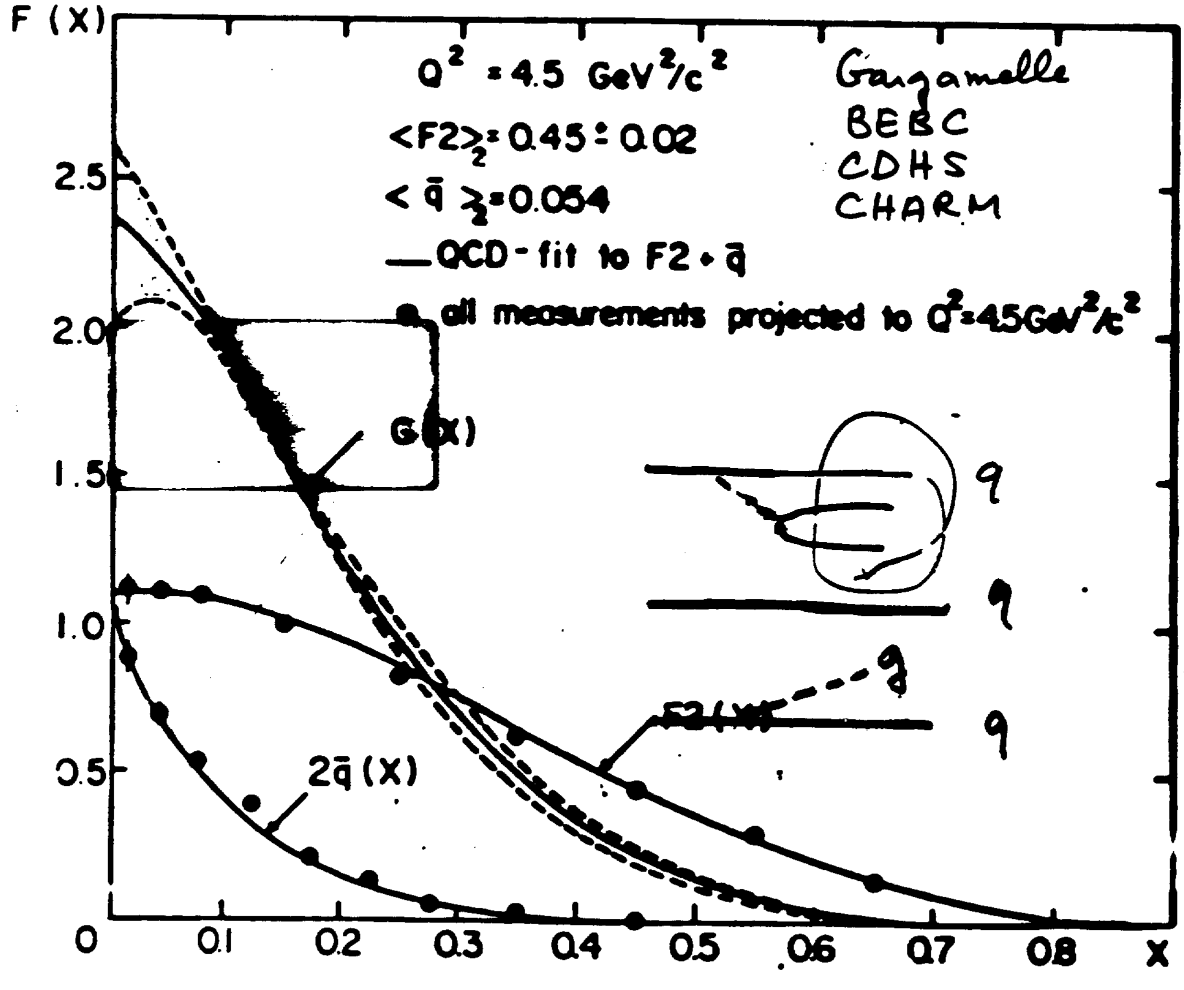
The UA1 detector
ElectroWeak Radiation



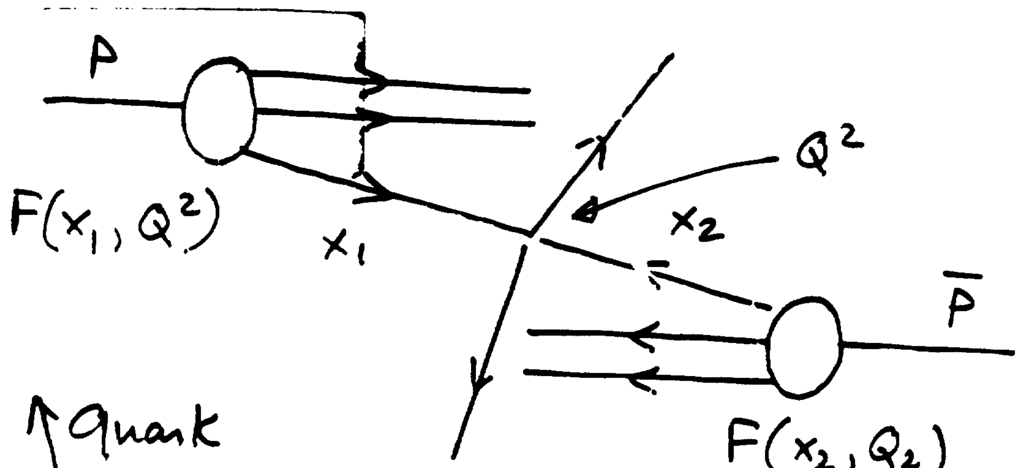
The CDHS detector



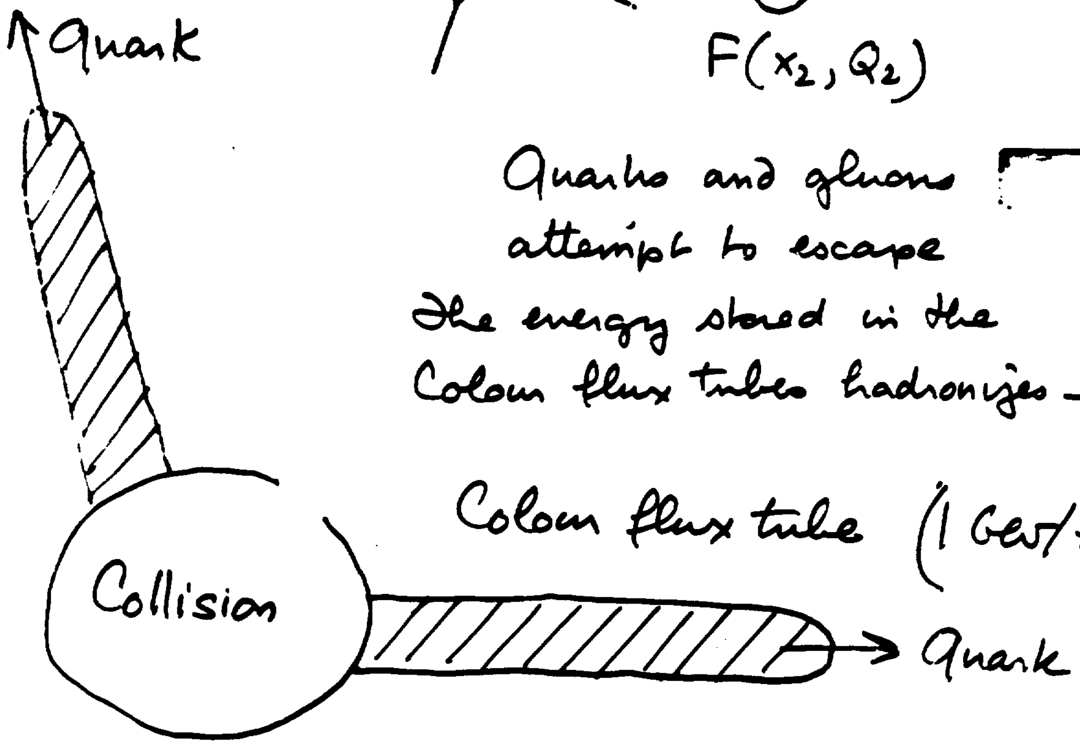
The quark map of the proton CDHS

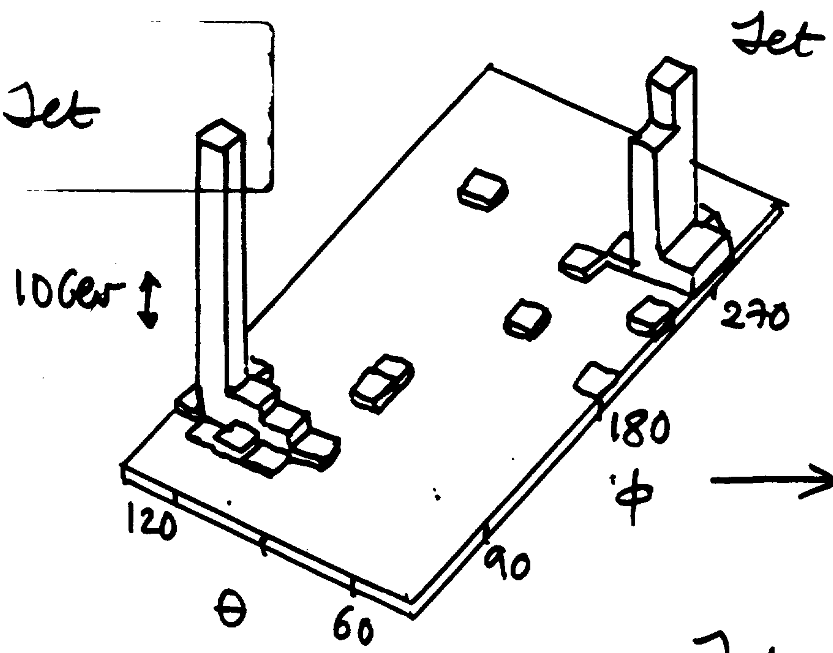


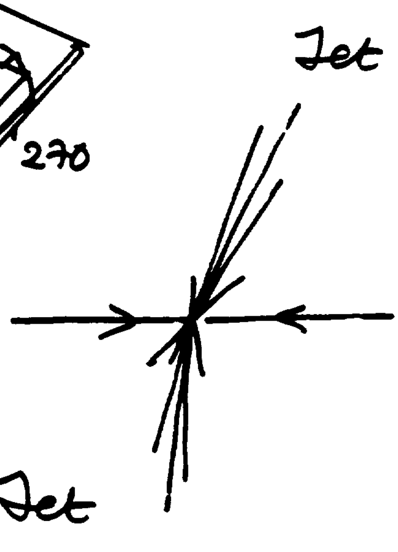
# Hadronic Jets




Quarks and gluons attempt to escape
The energy stored in the Colour flux tubes hadronizes → π



Transverse energy deposition

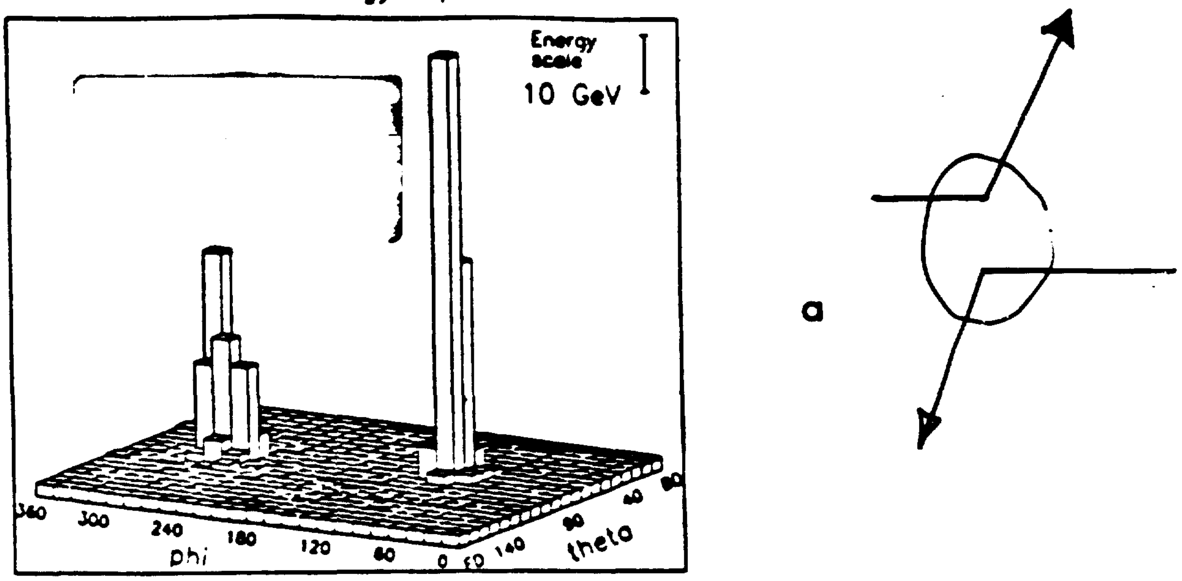
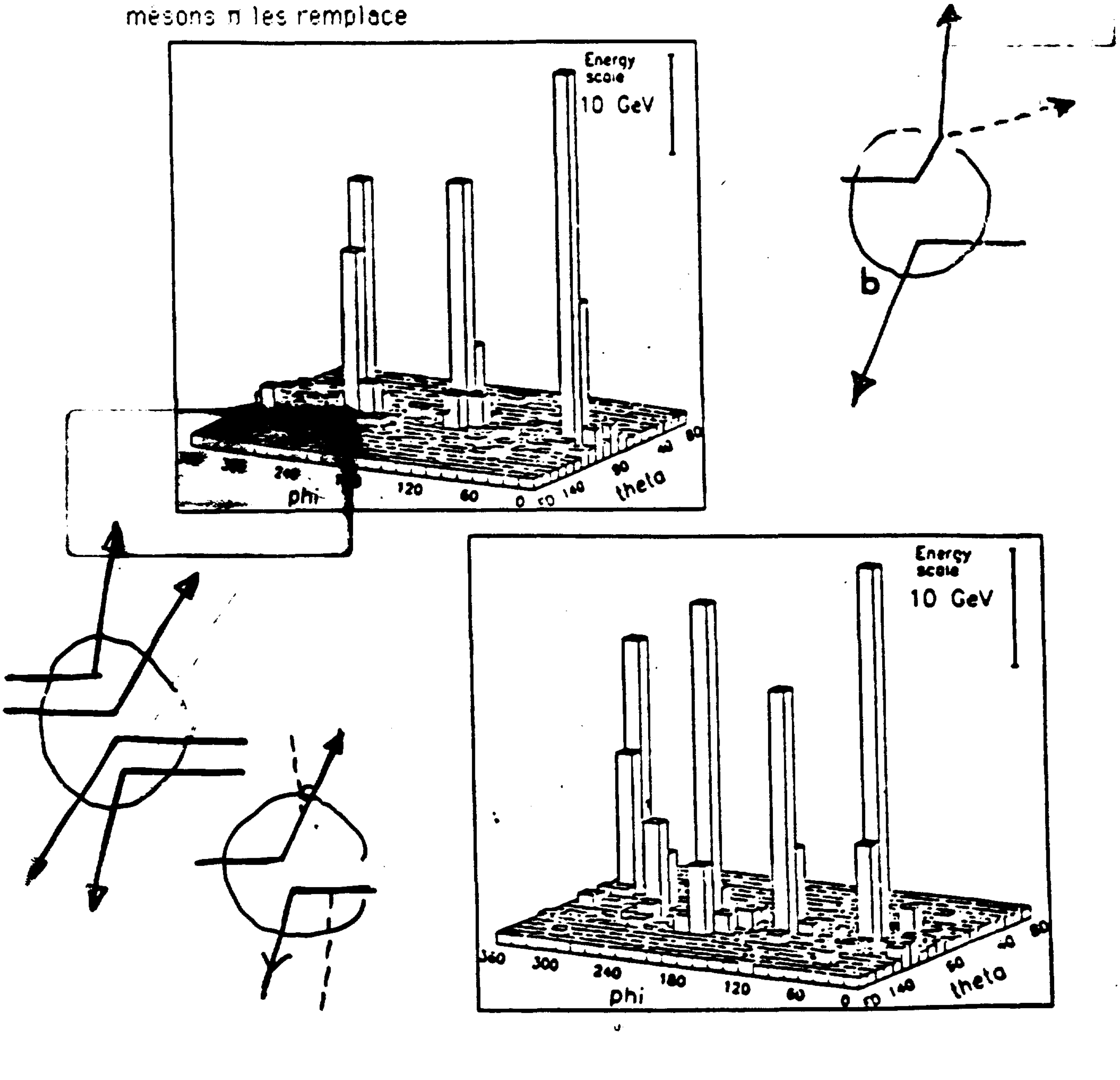
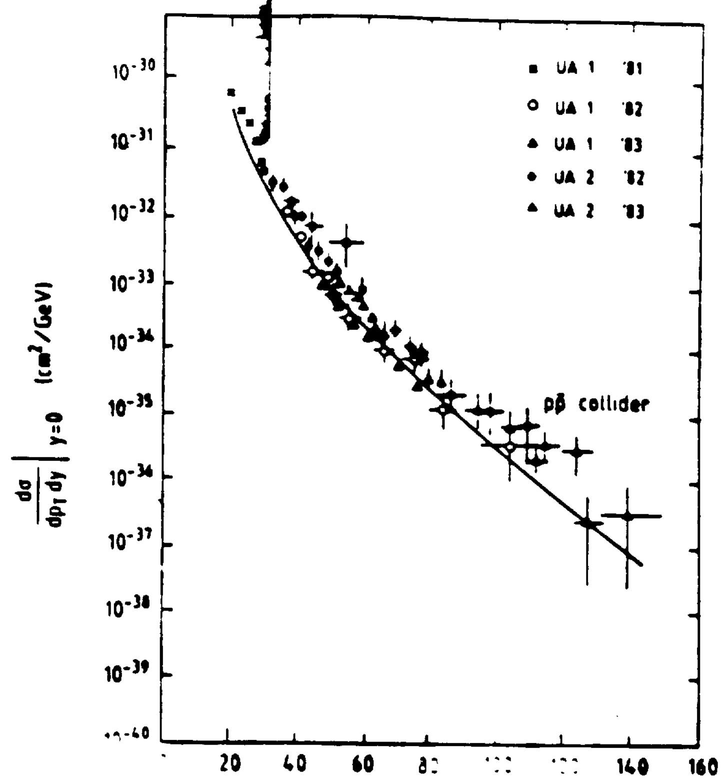



Figure 13. Exemples de jets hadroniques.Collision entre deux quarks.Rayonnement d'un gluon par un des quarks éjectés.Double collision entre quarks dans un collision proton-antiproton.On ne voit ni le quark ni le gluon mais la signature cinématique n'en est pas moins nette.Un jet de mésons π les remplace

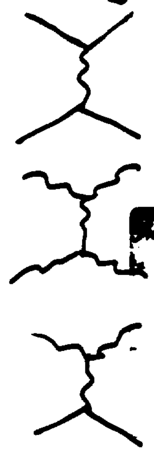


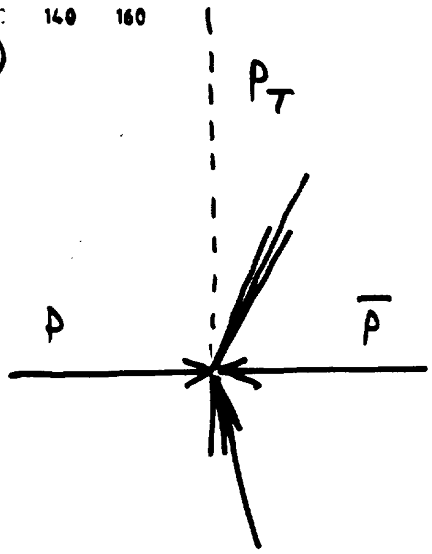
A success of QCD
a Gauge theory of colour
based on $SU_3$ symmetry

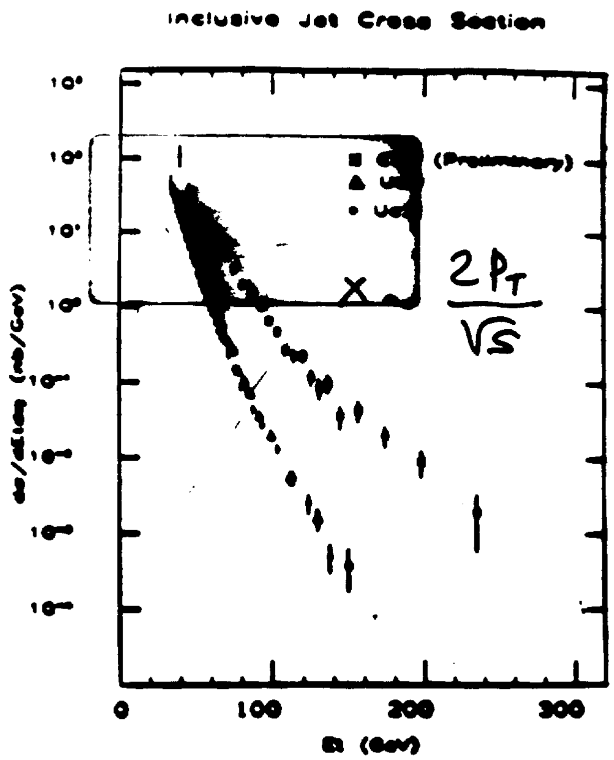



$p_t$ (GeV/c)

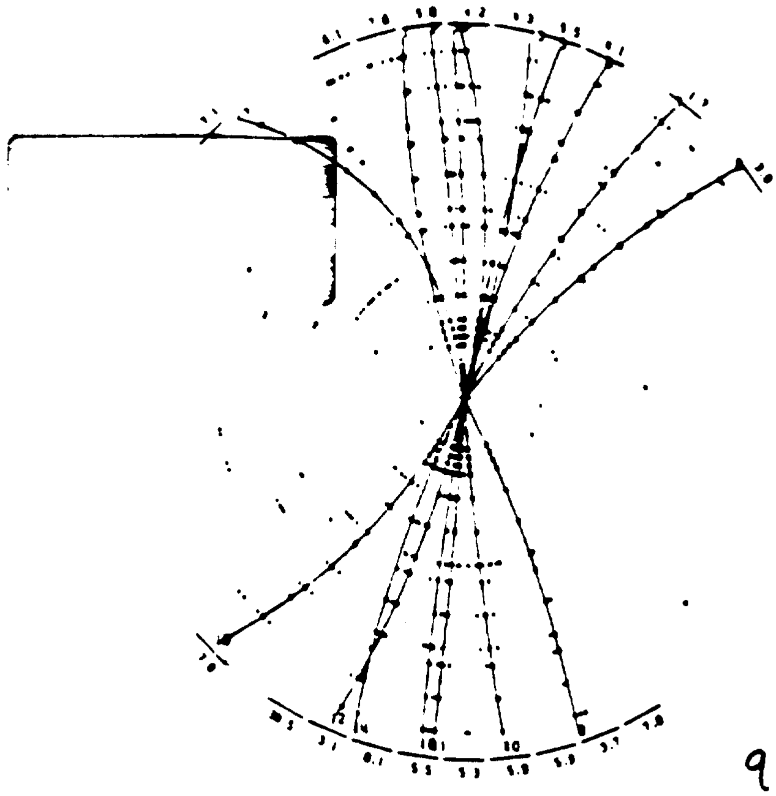
R ↔ B
R ↔ G
G ↔ B
8 (coloured gluons



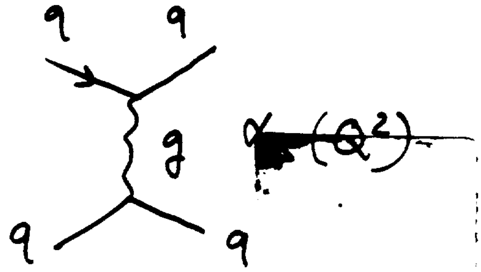



Hadronic jets
as expected from the
collision of
quarks, antiquarks
and gluons



$e^+e^- \to q\bar{q}$

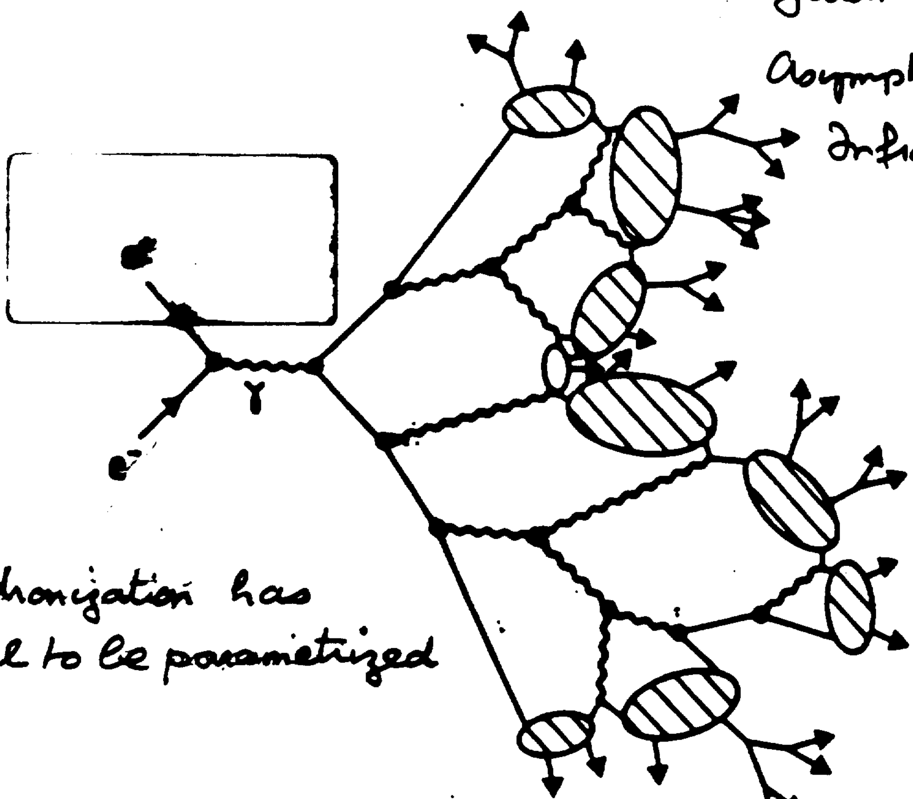



$\alpha(Q^2)$

Jets as they are seen
and what theorists can do

Coupling Weaker at short distance < $10^{-16}$ m
Stronger at large distance

Gluon self coupling
Asymptotic freedom
Infrared Slavery




Hadronization has
still to be parametrized

Over the past 35 years

Since the begining of CERN

First synchrotrons

Strange particles

~ 1 GeV

Super synchrotrons
used as Colliders

W, Z

~ 100 GeV

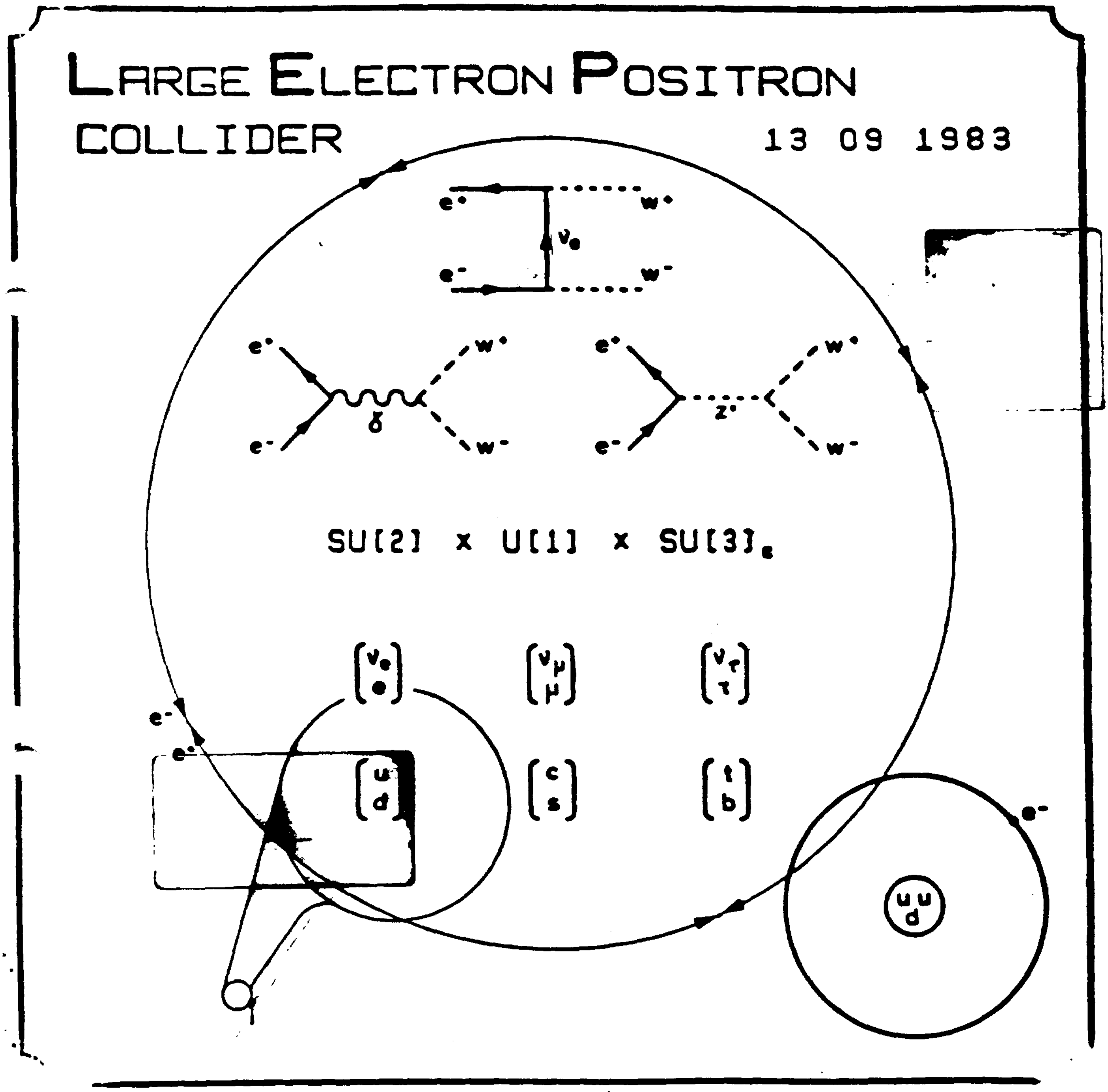
We have understood Weak interactions
We have understood Strong interactions
We have understood the proton quark structure

Standard Model
physics at $10^{-18}$ m

Where is the top ?
What is the Higgs ?
Why are they so many parameters ?

LEP is the ideal instrument to probe in depth
the Standard Model

~~On the~~ LEP Corner Stone
(1983)




A Plaque for alien excavators
of the future

What was the reason for building this monument?

The standard model is great

But

3 Different Couplings

Many masses

Why are the weak and the electromagnetic Couplings of the quarks and of the leptons so related.

Why 3 families of quarks and leptons

How is the primordial symmetry broken

Problems with Higgs mechanism

Bound state of hitherto unknown particles

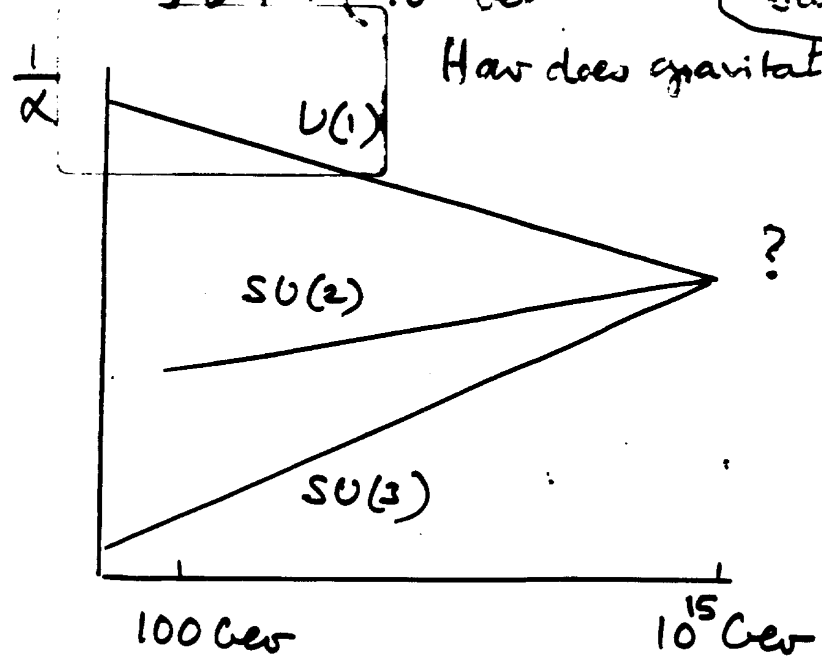
Supersymmetric partness

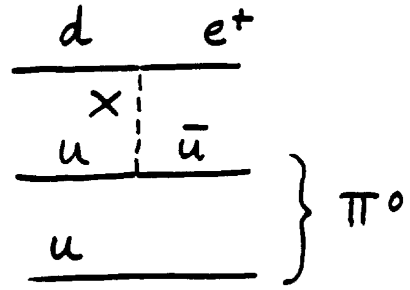
How does this fit within a higher symmetry

GUT's ($10^{15}$ Gev

Superstring

How does gravitation comes in $10^{19}$ Gev



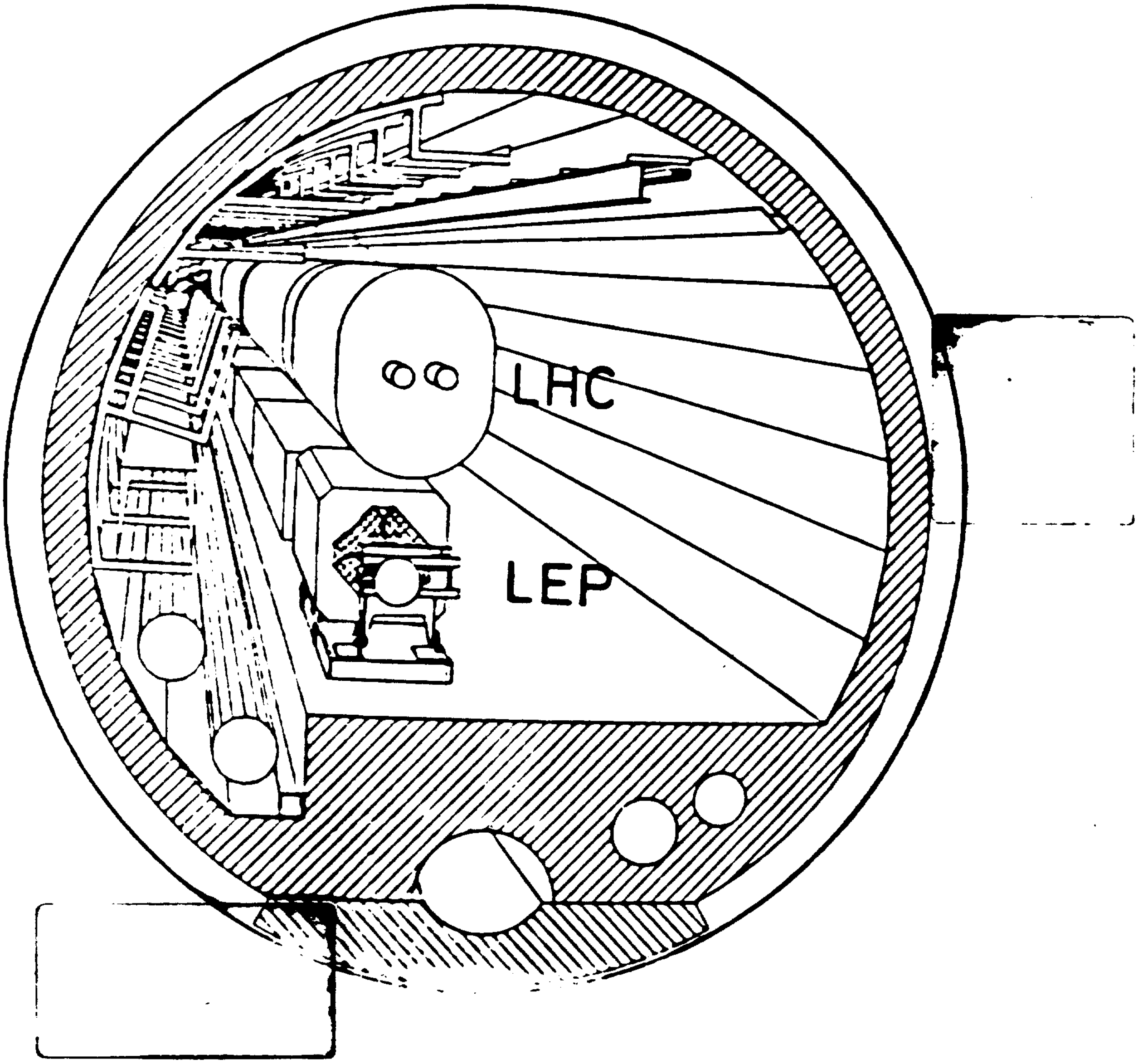

$m_X \sim 10^{15}$ Gev

$10^{31}$ years

Whatever way one looks at it new things have ~~to occur by~~ the time one reaches 1 TeV at the constituent level

SSC 40 TeV 3

PP 17 TeV




LARGE HADRON COLLIDER
IN THE LEP TUNNEL

At stake is the way Nature uses the Higgs mechanism
The origin of mass

Particles $\left\{ \begin{array}{l} \text{quarks} \\ \text{leptons} \end{array} \right.$ → Quantum fields

Interaction's are associated with fields

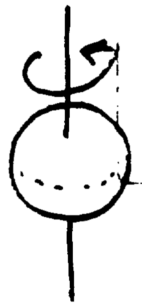
Quantum fields → particles

| | | | | |
|---|---|---|---|---|
| ElectroWeak | $\gamma$ | $W^+$ | $W^-$ | $Z^0$ |
| | (0) | (81 GeV) | | (92 GeV) |
| Strong (colour) | | $g$ | | |
| | | (0) | | |

Vector Bosons

All are vector (spin 1) particles

The quarks and leptons are spin 1/2 particles



$J = \hbar s$

Intrinsic Angular momentum

A quantum effect

Spin 1/2 → __Fermions__ Antisymmetric

half integer Atomic Shells

Integer Spin → __Bosons__ Symmetric

Spin 1 Laser beam

## Real and virtual particles

$\hbar = c = 1$ — Quantum relativistic world

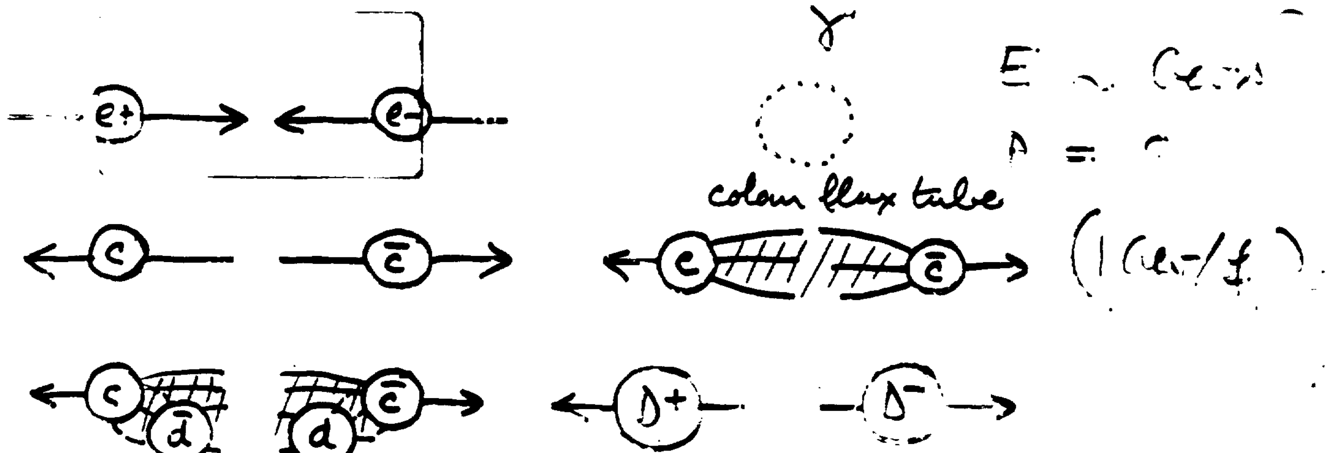
$$E^2 = p^2 + m^2$$

$$v = \frac{p}{E} \rightarrow 1 \quad \text{for massless particle}$$

$$\Delta E \, \Delta t \sim 1 \qquad \Delta p \, \Delta x \sim 1$$

The energy (momentum) can reach any arbitrarily high value over a small enough time (space) interval

During small enough a time (over small enough a distance) the relation $E^2 = p^2 + m^2$
can be violated
→ Virtual particle

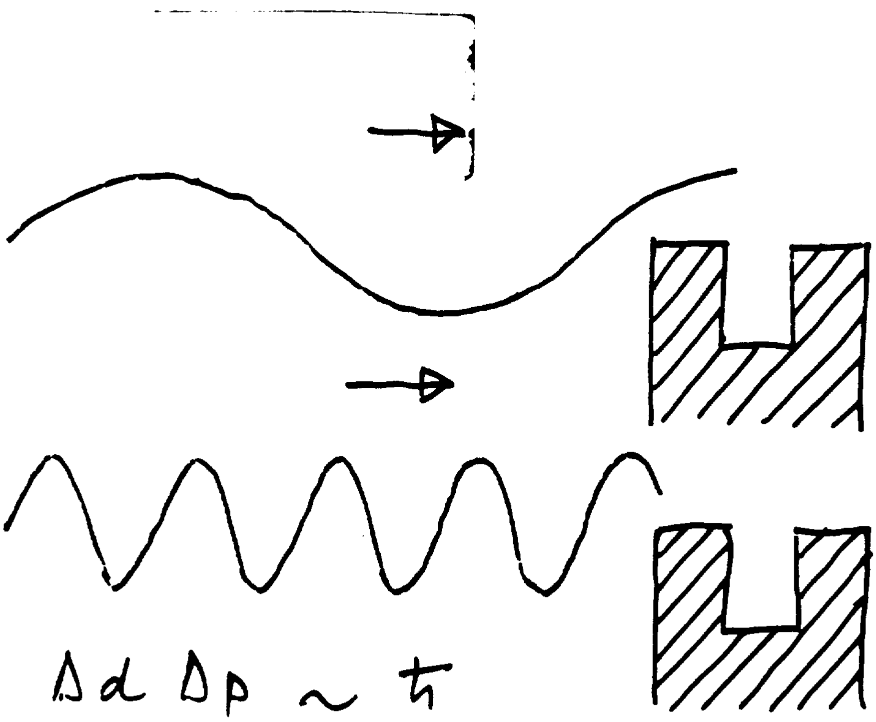



$e^+e^- \rightarrow D^+D^-$ in 6 frames
([illegible])

Ages of life in the quantum world

J26

## Structure and energy



$1\ \text{GeV} = 1.6 \times 10^{-10}\ \text{J}$

$M_p = 1.7 \times 10^{-27}\ \text{kg}$

$\lambda < d$

$\Delta d\, \Delta p \sim \hbar$

$\lambda\!\!\!^{-} = \dfrac{\hbar}{p}$ Small $d \to$ high $p$

In order to explore small structures one needs high energies

Small structure $\to$ Strong binding $B > c\,\Delta p$

In order to distort a small structure one needs <u>high energies</u>

100 MeV $\to 10^{-15}$ m 100 GeV $\to 10^{-18}$ m

Cosmic connection

Big Bang $E \sim T^{-1/2}$

100 MeV $\to 10^{-4}$ s 100 GeV $\to 10^{-10}$ s

Particle physics $\to$ The physics which prevailed at the beginning of the Universe

Going from Atomic physics to particle physics I (27)

One extra I 27

## The realm of relativity

We need very high energies  Atom ~ eV

100 MeV  100 GeV →

($10^{-15}$ m)  ($10^{-18}$ m)

pion mass  0.14 GeV  ($E_0 = mc^2$)

nucleon mass  0.94 GeV

The energies involved are much larger than typical mass energies  $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$

$\gamma = \frac{E}{mc^2} \gg 1$ → Full relevance of Relativity

$\tau = \gamma \tau_0$

Energy is freely transformed into matter and vice versa

Quantum mechanics  $\hbar \sim 1$

Relativity  $c \sim 1$

Causality

↓

Quantum Field Theory

Particle – antiparticle symmetry

Part 2, — b

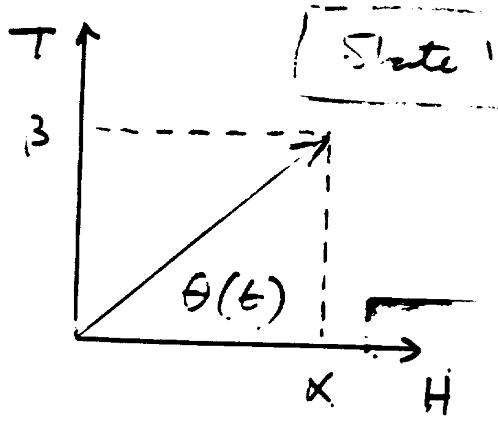
# The Quantum World

Classical view

Heads or Tails

Quantum view

State vector




$\alpha |H\rangle + \beta |T\rangle$

The dynamics is described by giving the rule for how the vector rotates with time

The state vector evolves deterministically. Indeterminism only enters when one tries to measure which state the coin is in

$|\alpha|^2, \ |\beta|^2$ probabilities

$x(t) \quad p(t) \longrightarrow \psi(x,t)$ Wave function

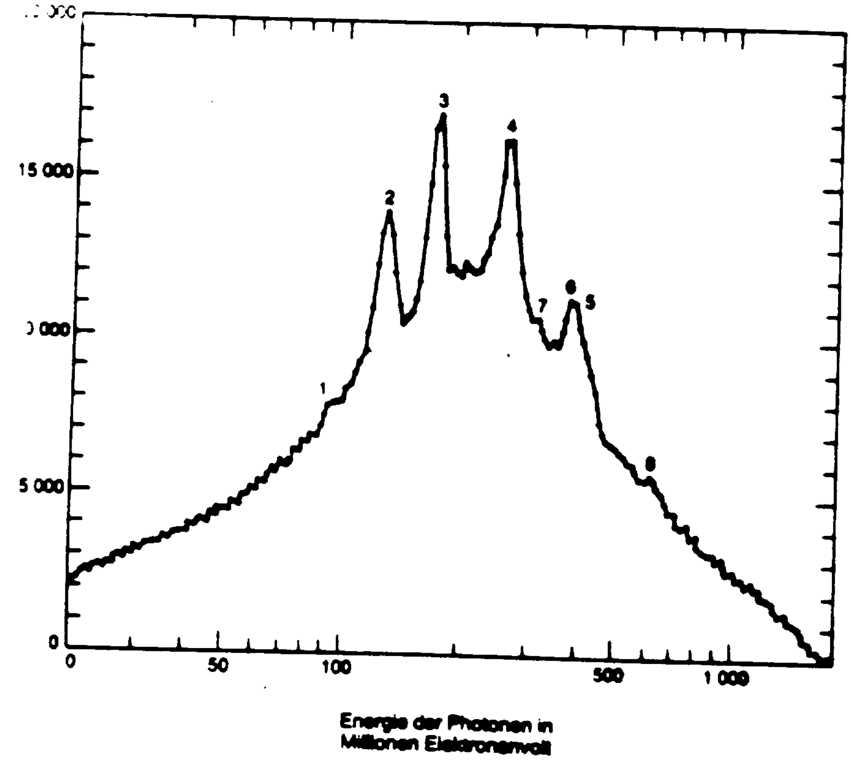
$$\boxed{\Delta x \, \Delta p \sim \hbar}$$

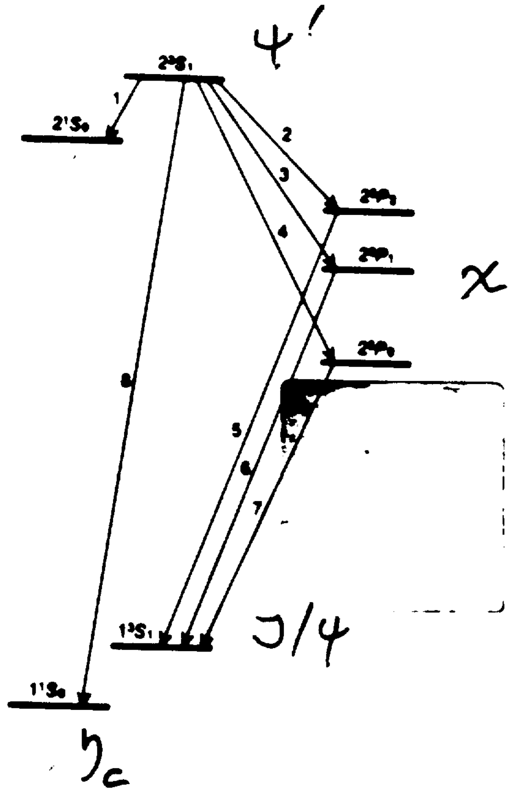
$$\hbar = 1.05 \times 10^{-34} \ \text{J.s}$$

$$A \approx 6 \times 10^{23}$$

$$0.3\,\mu \rightarrow 10^{-15}\ \text{s}$$

The atom already brings us into the Quantum World.




# Charmonium

The "hydrogen atom" at the quark level

## Sample of Baryons

Rosenfeld tables; Particle Data

| | | |
|---|---|---|
| $p$ | $uud$ | old timers |
| $n$ | $udd$ | |
| $\Delta^{++}$ | $uuu$ | Strong $\pi N$ decay; early fifties |
| $\Lambda$ | $uds$ | 51 (Cosmic Ray) |
| $\Omega^-$ | $sss$ | 64 (BNL) |
| $\Lambda_c$ | $udc$ | 79 (ISR) |

Weak decays

## Sample of mesons

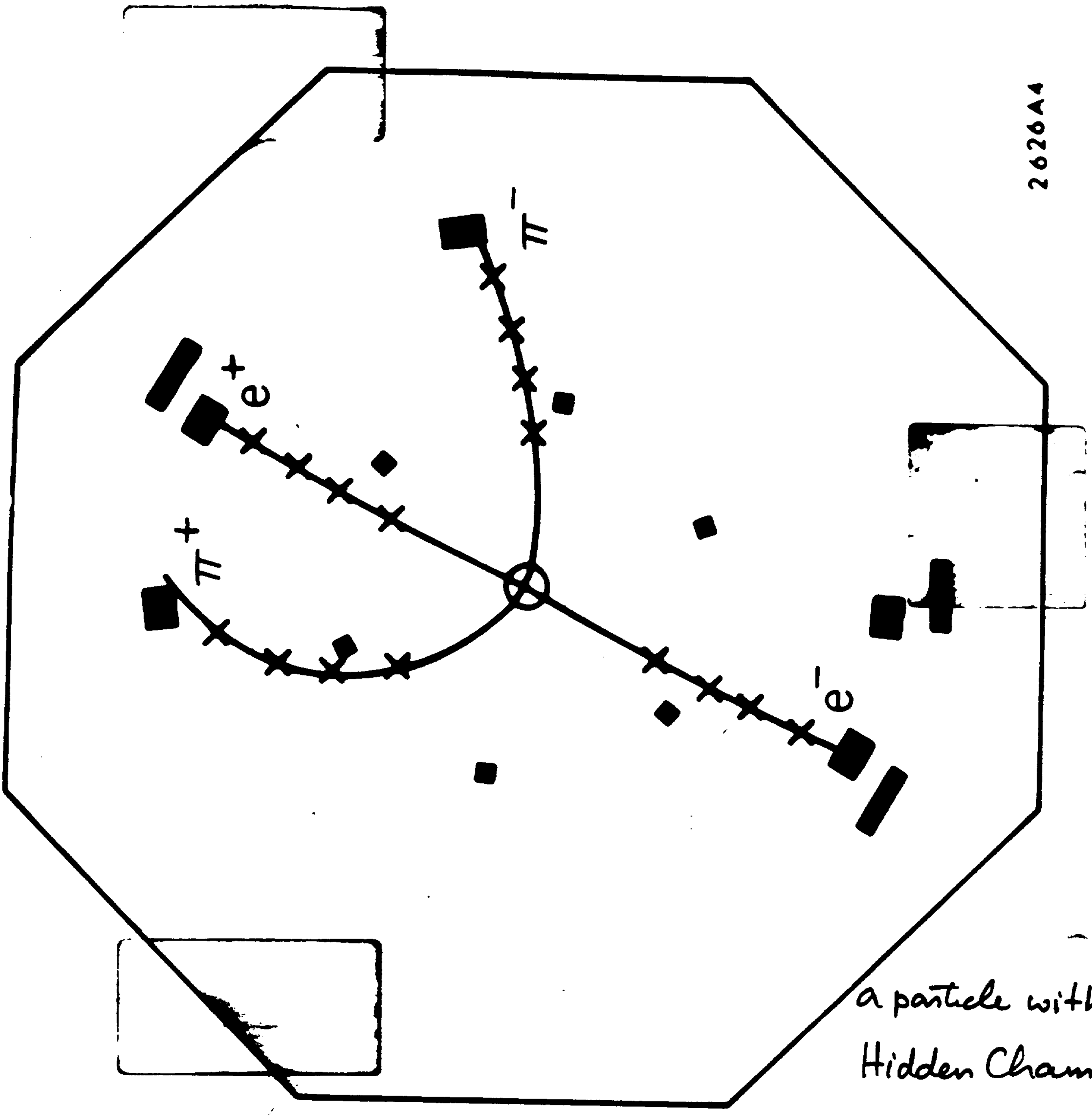
| | | |
|---|---|---|
| $\pi^+$ | $u\bar{d}$ | long expected (Yukawa) 47 |
| $K^+$ | $u\bar{s}$ | 46 (Cosmic Ray) |
| $\rho^+$ | $u\bar{d}$ | Strong $\pi\pi$ decay; early sixties |
| $D^+$ | $c\bar{d}$ | late seventies |
| $J/\psi$ | $c\bar{c}$ | 74 "revolution" |

(1000 times too slow)

The quark model brought order and simplicity to a hadronic world of seemingly high complexity ~ 200 particles named

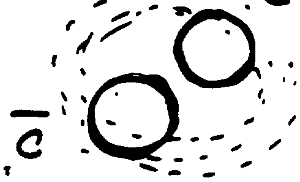
I/4 The discovery of a new charmed world






a particle with Hidden Charm

$\psi' \longrightarrow \psi + \pi^+ + \pi^-$



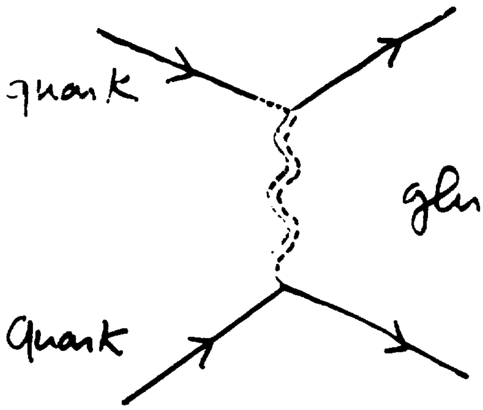

Quarkonium
(Charmonium)

The quarks are massive enough for a non relativistic atomic approach.

# The colour force

Quantum Chromodynamics

QCD




gluon $B\bar{R}$

8 gluons
Carrying
Non neutral Colours

$R\bar{R} + G\bar{G} + B\bar{B}$

Massless gluons

A priori Infinite range

**But** Colour cannot propagate into the vacuum

$$r \lesssim 10^{-15}\ \mathrm{m}$$

The vacuum behaves with respect to the colour field as a superconductor behaves with respect to a magnetic field

Visible objects $\rightarrow$ Globally neutral systems with respect to colour

3 quarks with three different colours $\longrightarrow$ Baryon

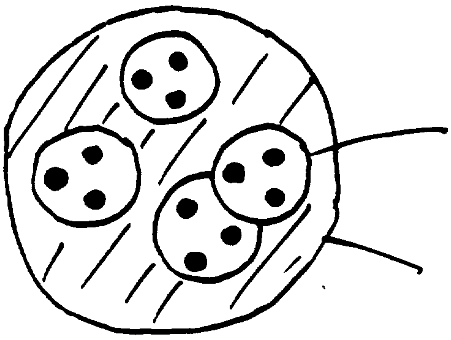
(Hadrons)

Quark and antiquark with opposite colours $\longrightarrow$ Meson

$\sim$ 200 particles named !

Other structures? Glueball, exotics ....

- The colour force binds quarks into hadrons but what binds the nucleus together?

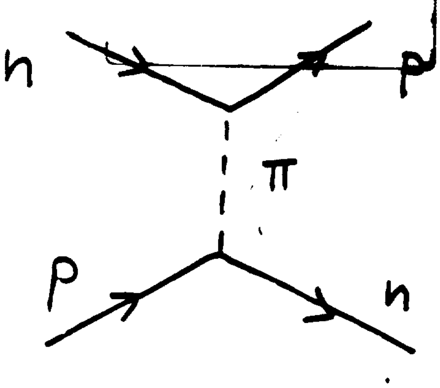


proton / neutron $\sim 10^{-15}$ m

Nucleus $\sim 10^{-14}$ m

The strong binding of the colour-neutral nucleons to form nuclei is due to residual strong interactions between their colour-charged constituents. It is similar to the residual electrical interaction which binds electrically neutral atoms to form molecules. It can be viewed as the exchange of mesons between the hadrons

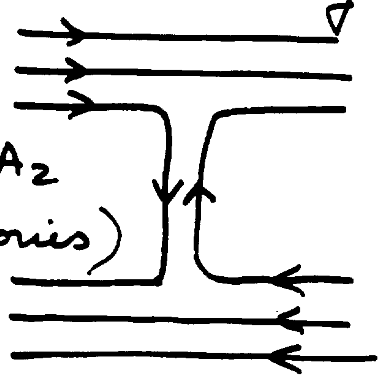
## Regge Models and Duality




$\pi$ +

$\rho, \omega, f_0, A_2$

(Regge trajectories)



Physics in the late fifties $\sim 10^{-15}$ m

in the late sixties $\sim 10^{-16}$ m

Dual diagram

Charge → Electromagnetic Interaction

Flavour → Weak interactions

Colour → Strong interactions

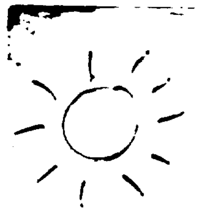
leptons — EM

W

quarks — S

Making the Sun work requires them all.

H → He



$\boxed{EM}$ Moderate strength, infinite range

ElectroWeak → Structure the atom

$\boxed{W}$ Moderate strength, Very short range

$r \sim 10^{-18}\,m$ → no structure

$\boxed{S}$ Important strength, in practice short range

$r \sim 10^{-15}\,m$

→ Structure the hadron

The dynamics down to $10^{-18}\,m$ → today

Grand Unified theory $10^{-31}\,m$

Superstrings Bring Gravitation into the Quantum picture $10^{-35}\,m$

# The relative role and strength of the fundamental interactions

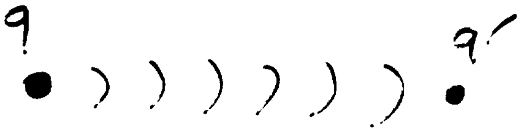
| | Gravitation | ElectroWeak | | Strong | |
|---|---|---|---|---|---|
| | | W | EM | F | R |
| Acts on | Mass. Energy | Flavour | Charge | Colour | Hadrons |
| Strength relative to EM taken as 1 | | | | | |
| Two quarks at $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | – |
| at $3 \times 10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | – |
| Two nucleons in a nucleus | $10^{-36}$ | $10^{-7}$ | 1 | – | 20 |

Gravitation is negligible in today's particle physics

Weak interactions were weak in Nuclear physics

Strong forces become weak at short distances !

## Interactions



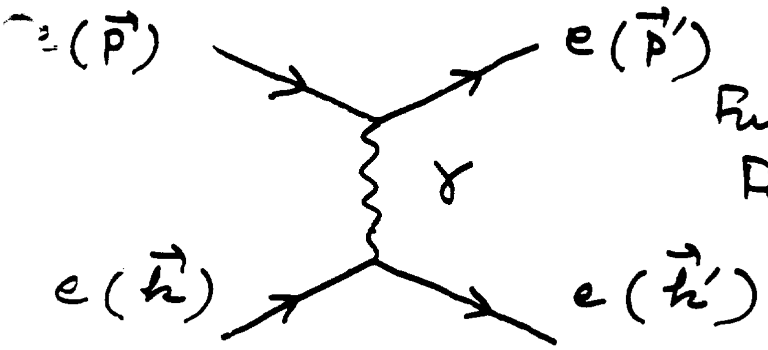

$$E = \frac{q}{r^2}$$

$$f = q' E$$

The electromagnetic Interaction

Charged particles are at the origin of the Electromagnetic field $E, H$

This field influences other charged particles




First encounter with Feynman Graphs

The Quantum view

Electricity and Magnetism clearly one at high frequency

Maxwell Equations

$$\nabla . D = 4\pi \rho$$

$$\nabla \times H = \frac{4\pi}{c} J + \frac{1}{c}\frac{\partial D}{\partial t}$$

$$\nabla \times E + \frac{1}{c}\frac{\partial B}{\partial t} = 0$$

$$\nabla . B = 0$$

Lorentz Invariance
(Relativity)

Quantum mechanics

↓

Quantum field theory

Gauge Invariance

$m_\gamma = 0$

Long range force $E \sim r^{-2}$ $\phi = C^{st}$
holds the atom together

I (19)
I 1.

J. J. Thomson 1907

"There is indeed one part of Physical Science where the problems are very analogous to those dealt with by the metaphysicians .... To some men (and women) this side of physics is particularly attractive. They find in the physical Universe with its myriad phenomena and apparent complexity a problem of inexhaustible and irresistible fascination. Their minds chafe under the diversity and complexity they see around them, and they are driven to seek a point of view from which phenomena as diverse as those of light, heat, electricity and chemical action appear as different manifestations of a few general principles"

The Dream is Alive!

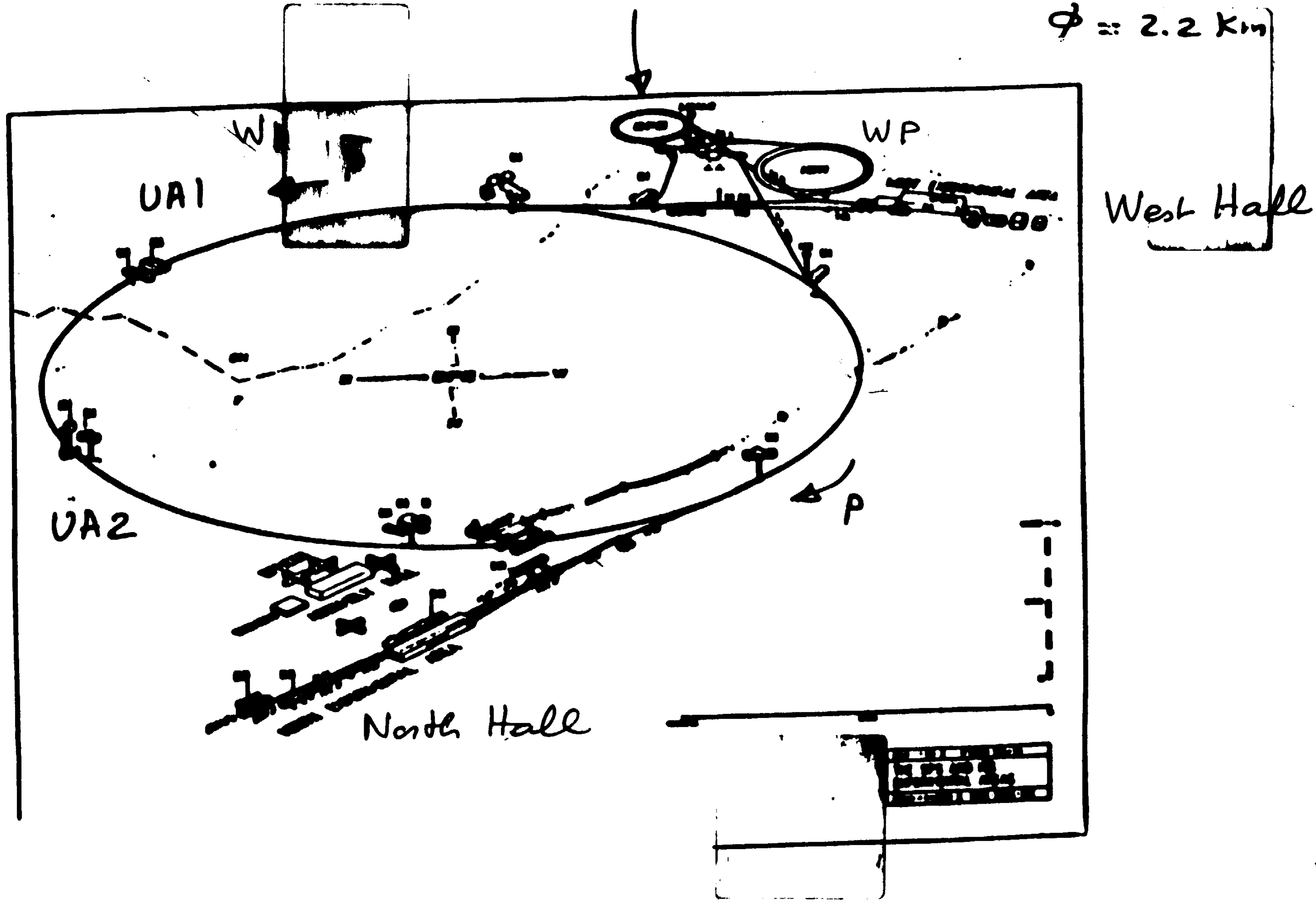
~~Many~~ particle
A unique (gauge) principle

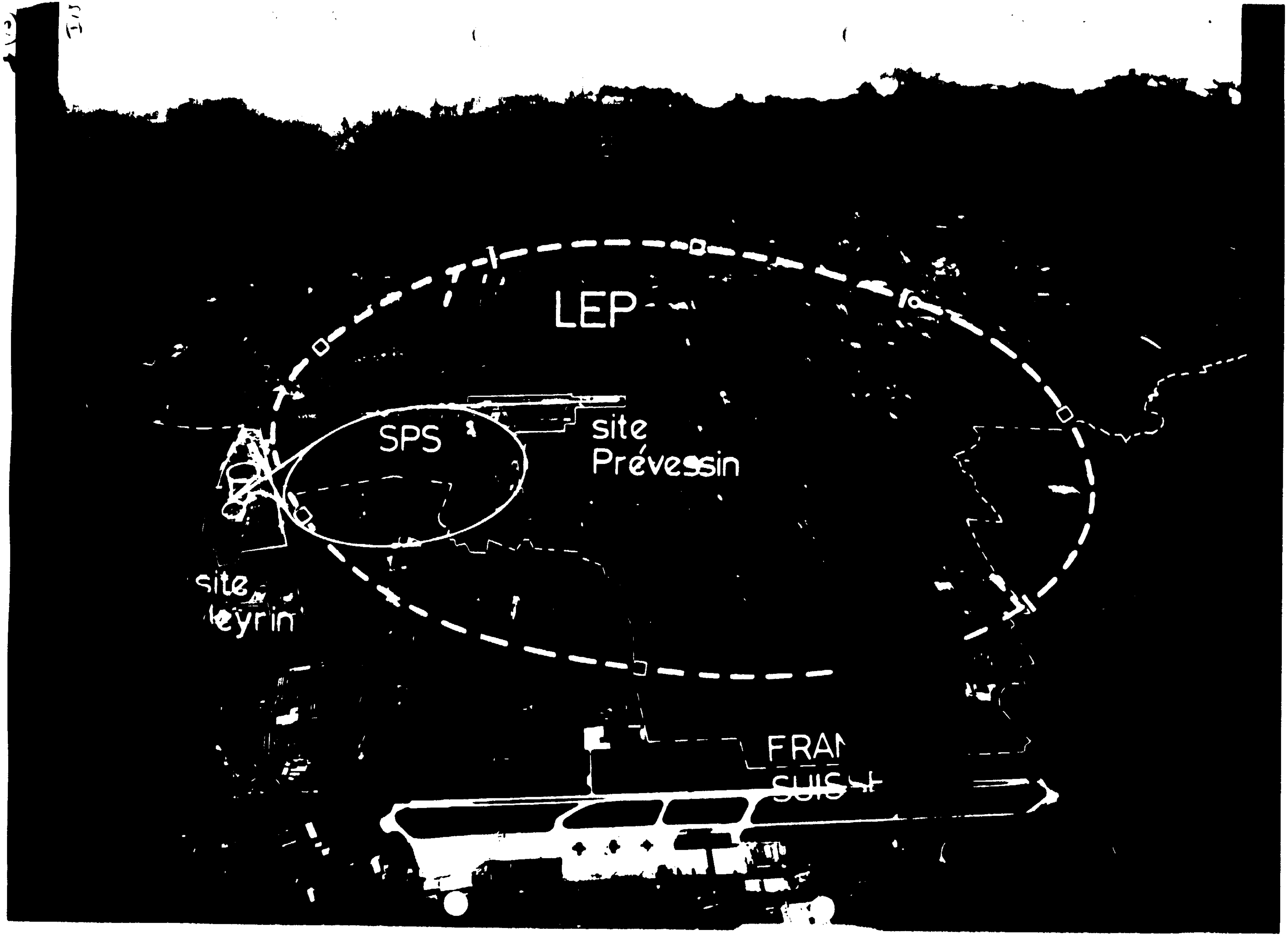
Unity and simplicity in a world of seemingly high Complexity

$$e\,\bar{\psi}\,\gamma_\mu\,\psi\,A^\mu$$

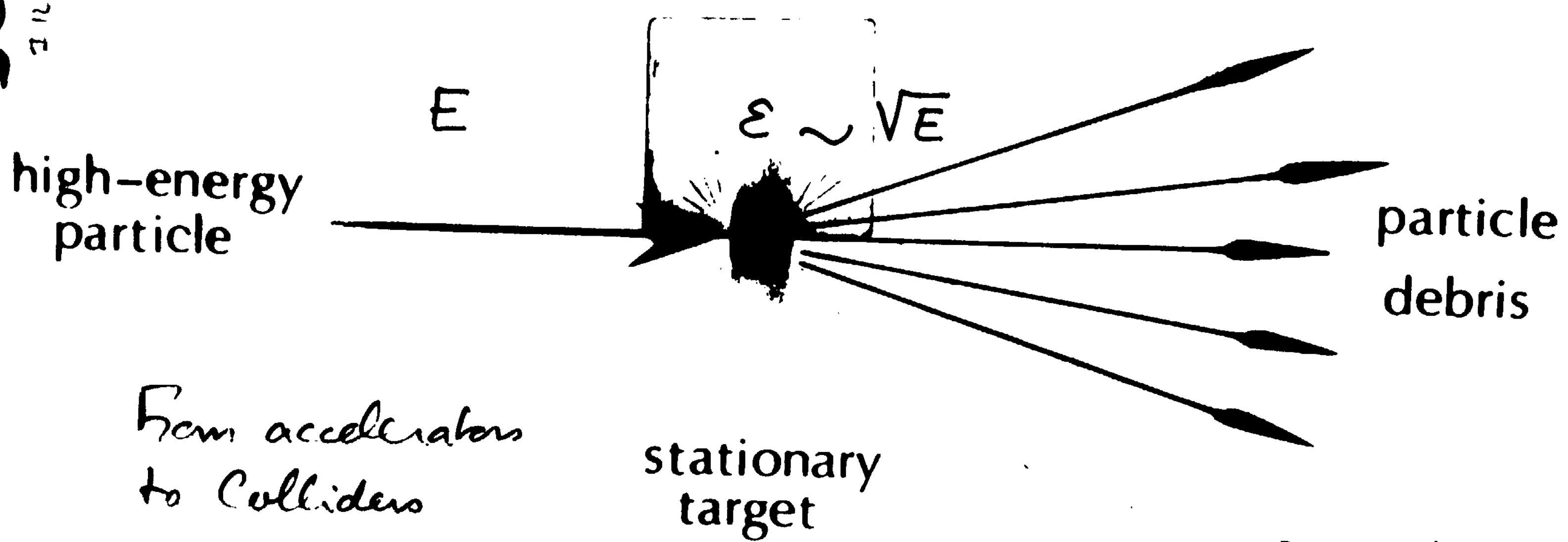
Electricity
Magnetism
Optics, Radio
The atom
and Chemistry

CERN SPS
1976 450 GeV
$\phi \approx 2.2$ Km

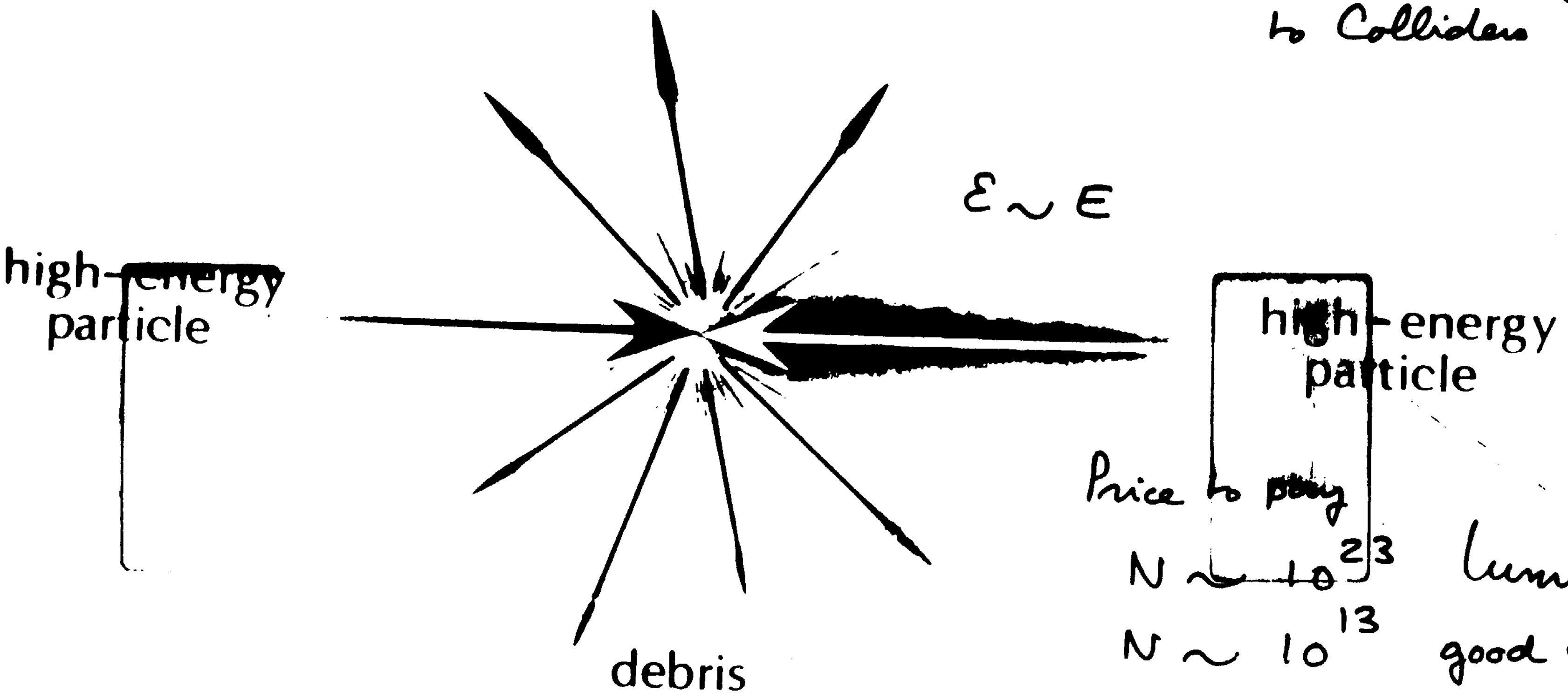



LEP
SPS
site
Prévessin
site
eyrin
FRAN
SUIS

From accelerators to Colliders




From fixed targets to Colliders.




Price to pay

$N \sim 10^{23}$ luminosity

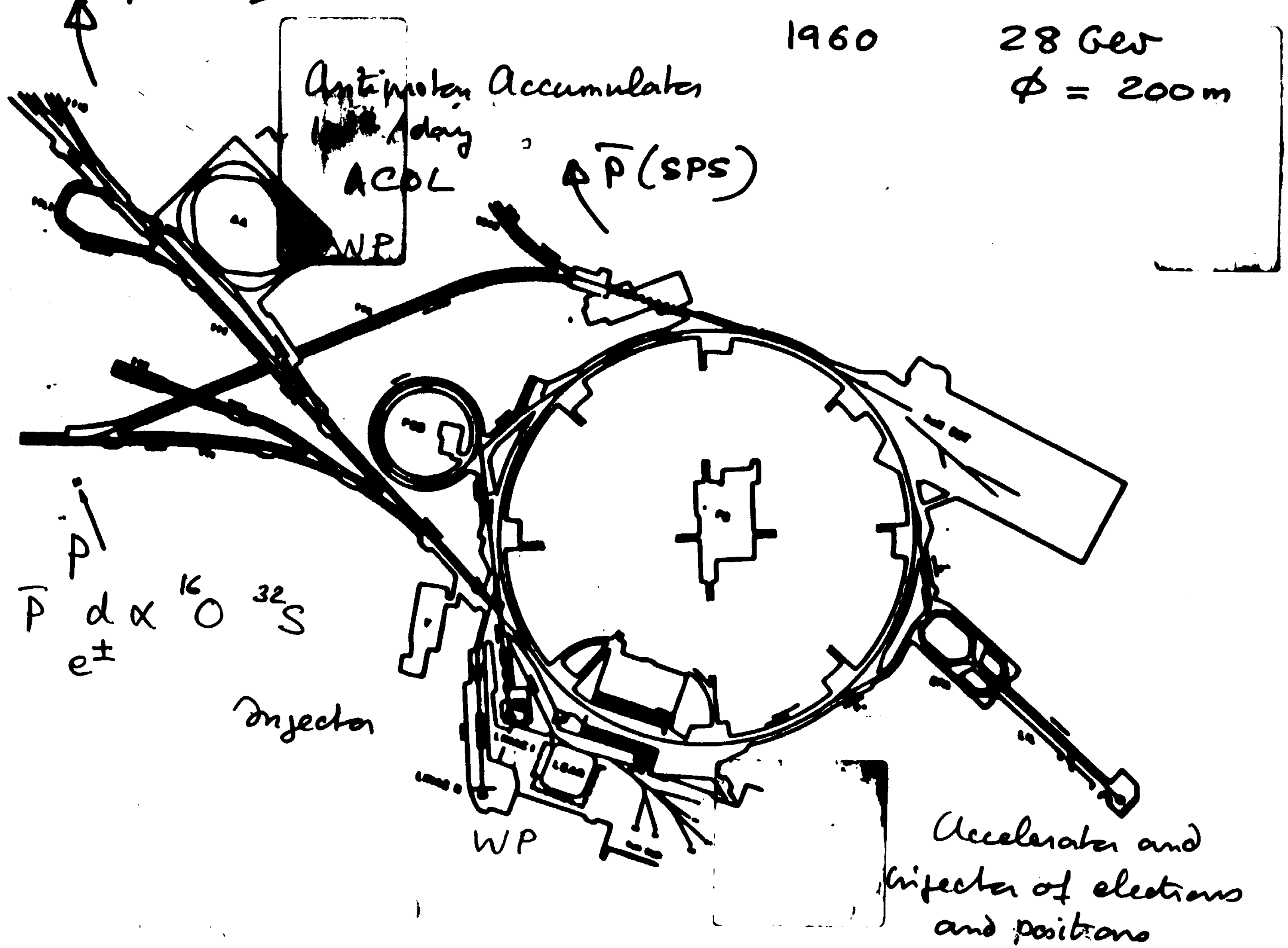
$N \sim 10^{13}$ good vacuum

$N = L\sigma$

# CERN - PS

1960 28 GeV

$\phi = 200\,m$



We see only as far as our instruments go

1947

Emulsion Experiment

Cosmic Ray event

$\pi \; \mu \; (\nu)$ decay

$\pi \sim 10^{-8}$ s

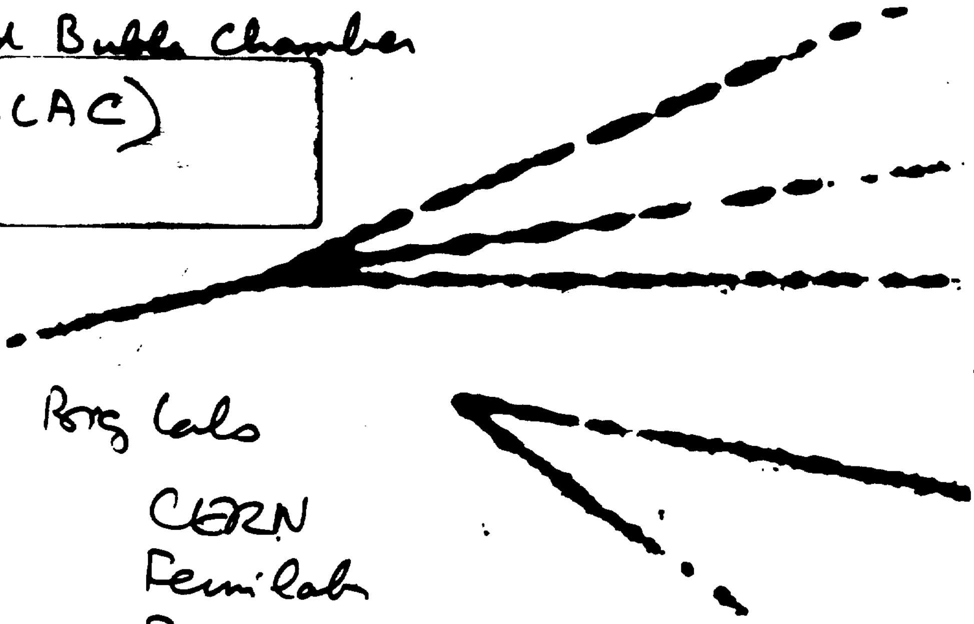
$\mu \sim 10^{-6}$ s


University Group Bristol

Present — Tracking Charm in photoproduction

$\tau \sim 10^{-13}$ s

Hybrid Bubble Chamber (SLAC)



Big Labs

CERN

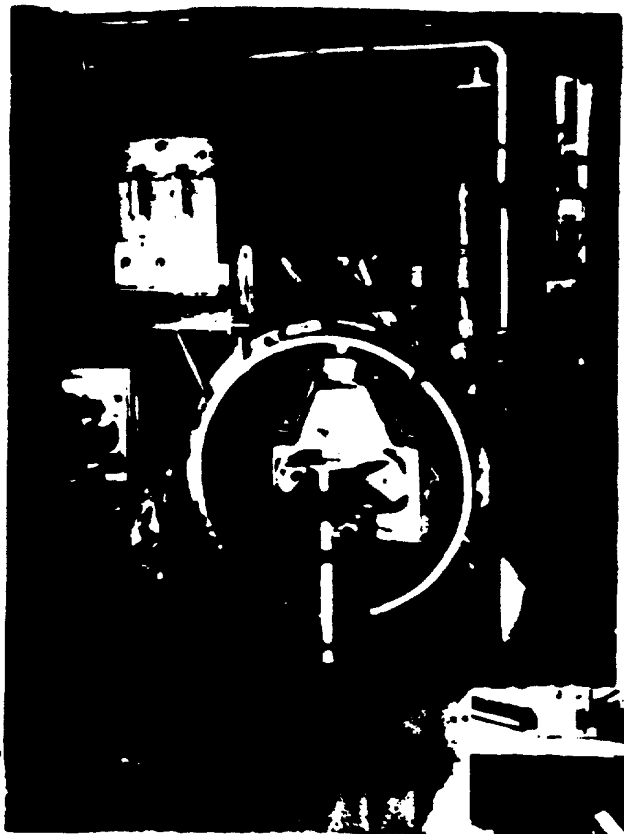
Fermilab

SLAC

JC I''

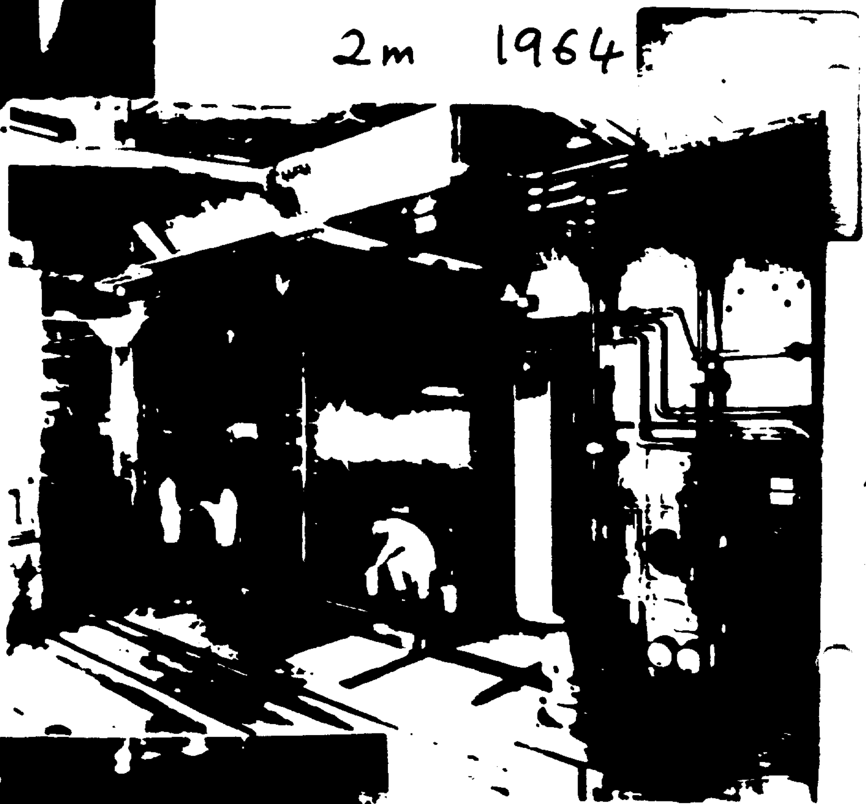
The evolution of Bubble Chambers

a 30 year adventure



81 cm 1961

2m 1964



Compare relative size of instrument and user.

BEBC 1977


The ride of particle physics

At present Museum items

The November revolution 74 *

J/ψ (a $c\bar{c}$ bound state)

Discovery of the τ lepton

Discovery of Charmed particles — mid seventies

Discovery of the Υ

Is there a Grand Unified Theory (proton decay!)

The rules of multiparticle production are spelled out

Large $p_T$ phenomena → Jets

The Quark "Rutherford" experiment

The gluon is seen in $e^+e^- \to$ jets

600 GeV — Discovery of the W and Z * early eighties

The jets come of age

particles with Beauty

Are Superstrings a TOE

C.P violation comes of age ($\varepsilon'$)

EMC; ~~Peculiar features~~ in relativistic heavy ion collisions — mid eighties

(In search of the Quark-Gluon plasma) — limits

The Universe until $10^{-5}$ s.

Weak interactions have been understood

Strong interactions have been understood

The proton quark structure has been understood

Fascinating perspective have been opened

A new world at $10^{-19}$ m?

About Forty years of particle physics

A Beautiful Crop of results

A Much deeper understanding of Nature

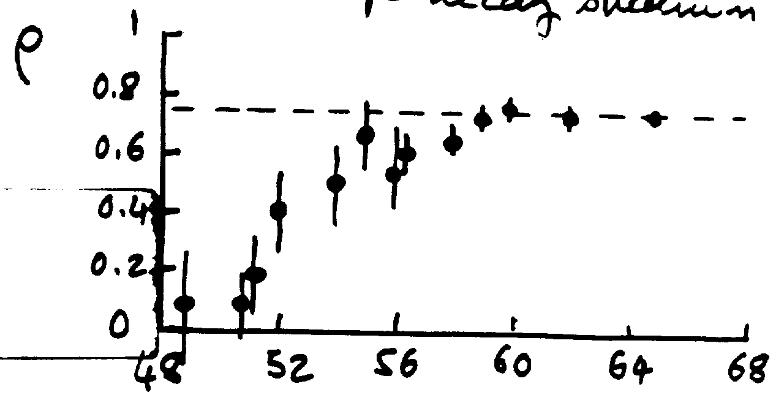
A Beautiful example of
International Collaboration

The two laws of the physicist of T. D. Lee -

(i) Without experimentalists, theorists tend to drift

(ii) Without theorists, experimentalists tend to falter

$\mu$ decay spectrum




V-A theory $\rho = 0.75$

Remember November 74 and the many
"explanations" for the J/ψ

A Scientist commonly professes to base his beliefs on observations, not
theories. I have never come across anyone who carries this profession into practice.
Observation is not sufficient. Theory has an important share in determining beliefs

A. S. Eddington

# The present basic Constituents

6 × 3 quarks
6 leptons

What is the world made of

$$\begin{array}{cccc} 2/3 & \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} & 0 \\ -1/3 & & & -1 \end{array}$$

Nucleons p (u u d) n (u d d)

Strange particles $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ particles of different "flavours"

particles with charm and beauty

$\begin{pmatrix} t \\ b \end{pmatrix}$. $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Still searched for !
$m_t > 40\ M_p$

Why does nature reveal the pattern (Who ordered the muon?
I. Rabi

Quarks carry "colour" R G B

Quarks and leptons are "point like" particles
$r < 10^{-18}$ m , probably much less

They are described by Quantum fields
→ particles and antiparticles
Same mass, opposite charges, flavours and colours

I (
I 7

# How did it happen

CERN (54)

The birth of particle physics Early fifties

The challenge of the Nuclear force

The strange Cosmic Ray events

The antiproton is discovered *

The strangeness rules are understood

GeV The π - Nucleon interaction is understood

The Weak interactions come of age

(Parity violation) * Late fifties

What is the structure of the proton? *

7 GeV The particle explosion Early sixties

The symmetry pattern is dicovered

The eightfold Way ($\Omega^-$) * Mid-sixties

The Quark hypothesis

The elusive asymptopia – the Bootstrap idea

The two neutrinos *

Regge Models and Duality

The violation of CP invariance *

Deep inelastic electron scattering late sixties

are partons quarks?

25 GeV
60 GeV

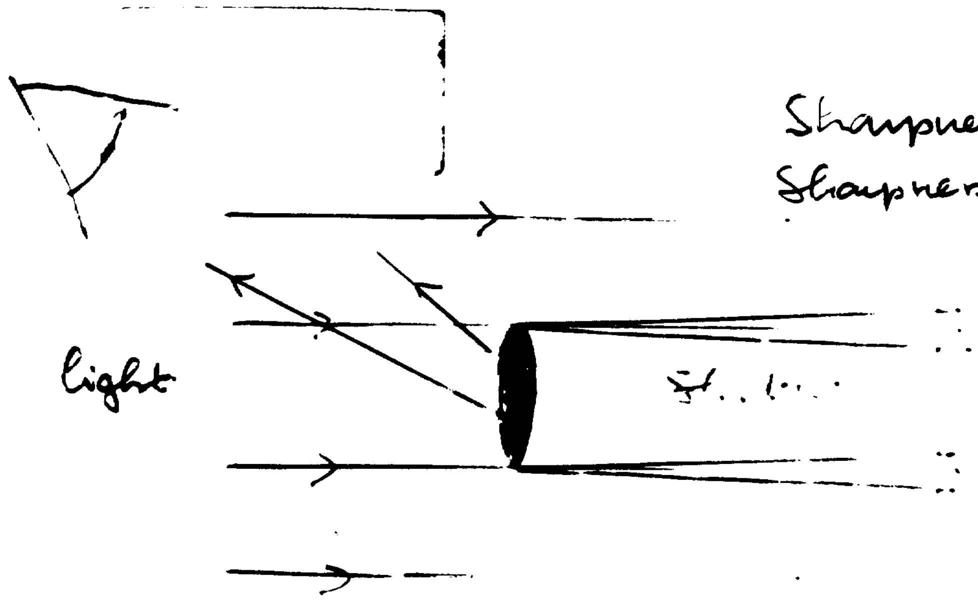
The quark map of the proton

Asymptotic freedom (QCD) Early seventies

Neutral Current interactions

ElectroWeak theory vindicated 71, 73 *

How does one "see" all these?

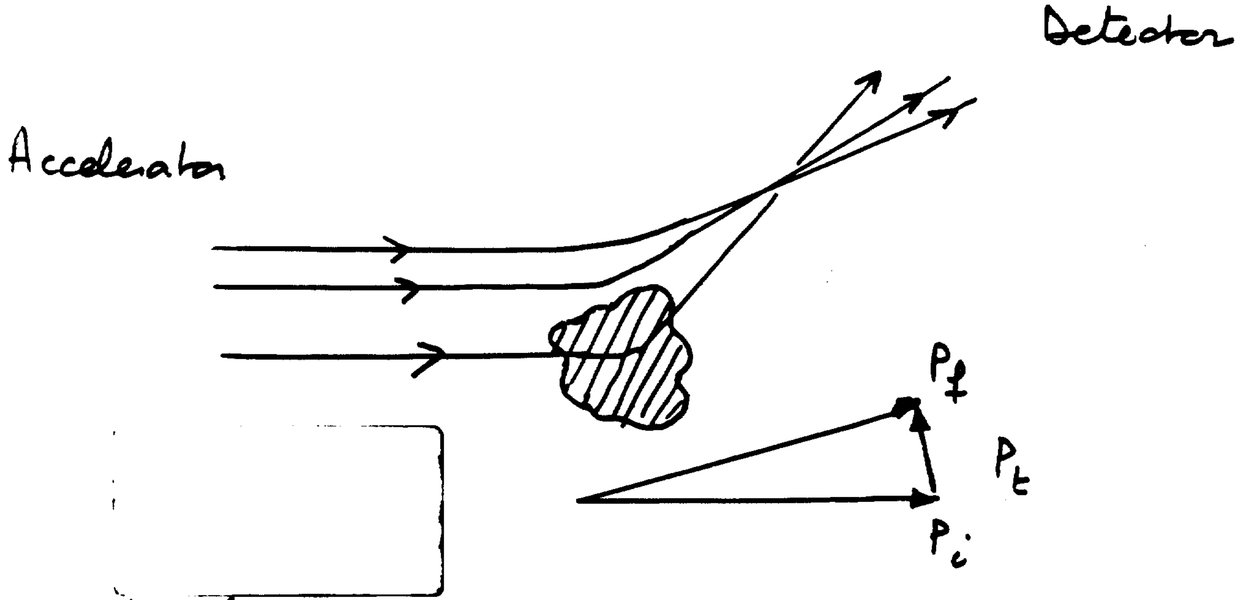



Sharpness of shadows
Sharpness of images

$$\theta = \frac{\lambda}{D}$$

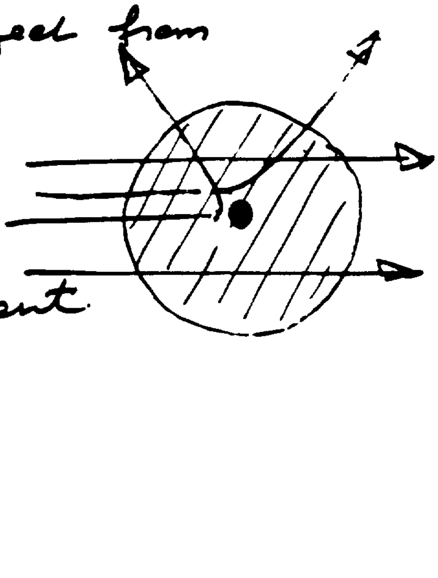
$$\lambda \ll D$$

The diffractive analogy




The higher $P_t$ the better one can determine the shape and structure of the object from the scattering pattern.

high $P_t \rightarrow$ high energy



The Rutherford Experiment

3c
15

SLAC 2 mile long accelerator

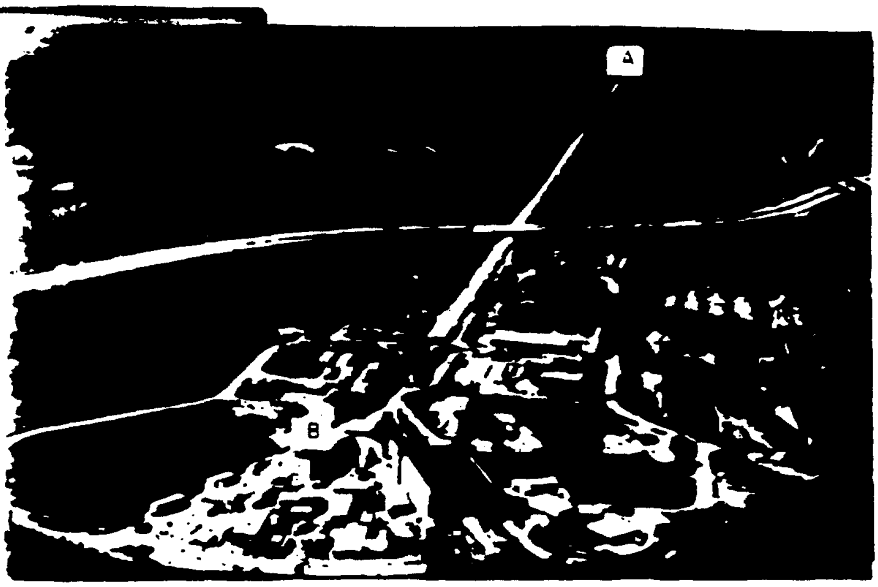
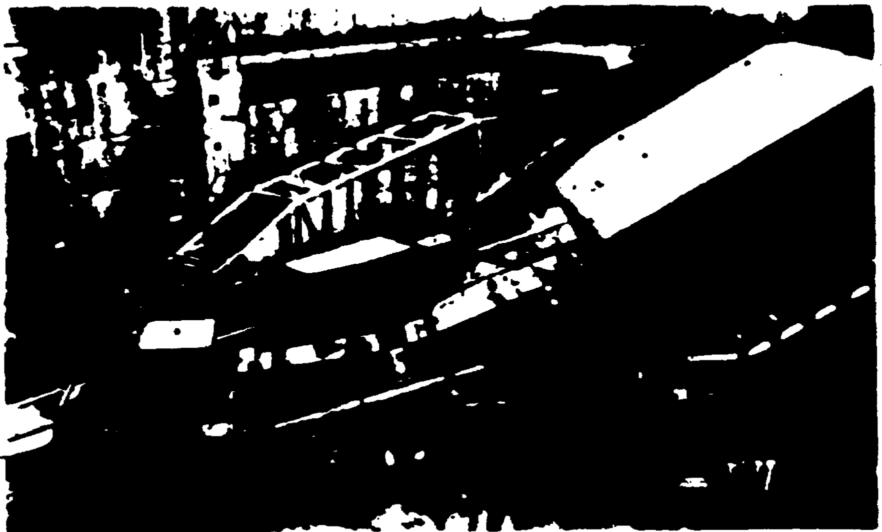



**Photo 6A** *SLAC 2 mile accelerator of electrons* Stanford Linear Accelerator of electrons (SLAC) in California. This is like a gigantic television. The back of the tube is at A. Electrons accelerate along the tube which is two miles long and the 'screen' consists of detectors in the building at B. (*Courtesy Stanford University*)



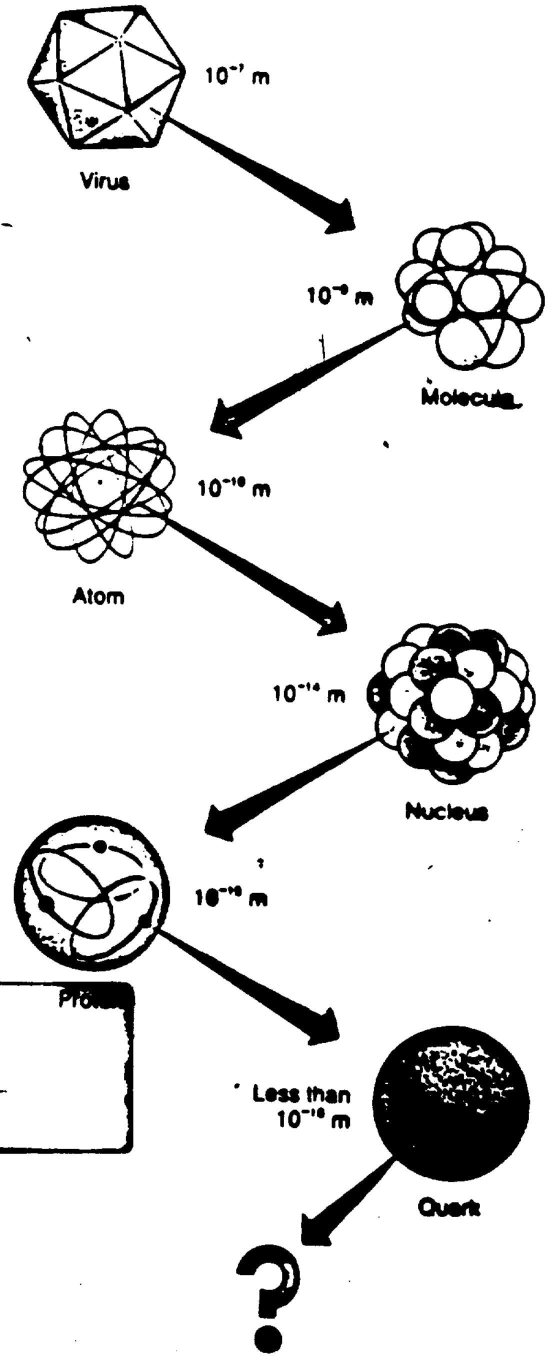
[illegible] *detectors at SLAC* (*Hall B in photo 6A*). These are the [illegible] referred to in photo 6A. A target of protons sits at the extreme left of [illegible] picture and electrons enter from the left, are scattered, and then detected. ([illegible] *University*)

What was required to first see point like quarks within the proton (1968)

# The different levels of structure

Classical

Quantum



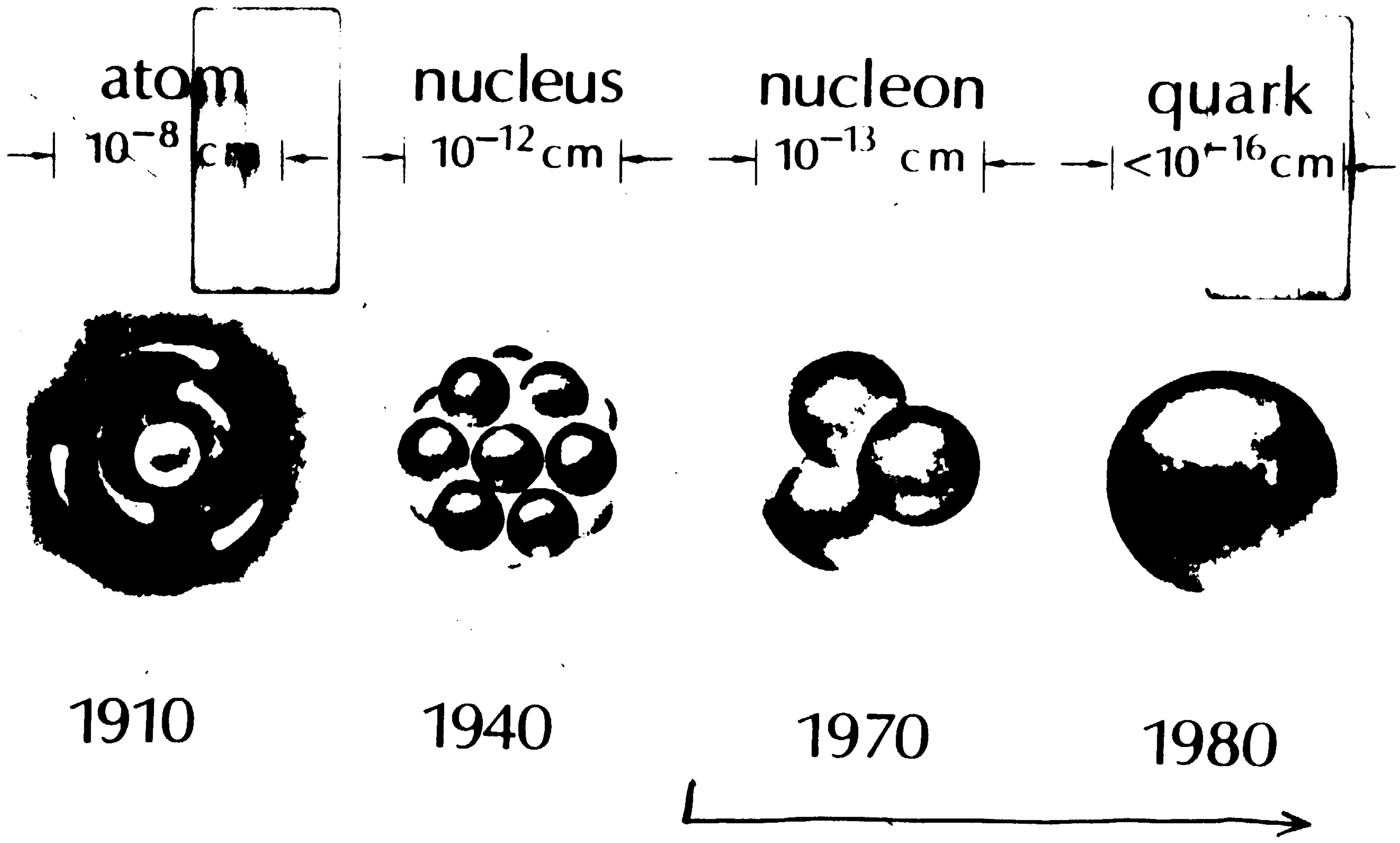

$10^{-10}$ m

$10^{-14}$ m

$10^{-15}$ m

$< 10^{-18}$ m

At present, with quark and gluon collisions, We probe the structure of matter at $10^{-18}$ m




particle physics
as we practice it today

What is the structure of the proton?

# Particle Physics

(i) What is it ?

What motivates it ?

How does it look to day ?

How did it develop ?

eighties !

TH 4427 (86)

~~Higgs~~

Jets

" Highlights of 25 Years of Physics at CERN "

L. Van Hove and M. Jacob PR 62, 1 (80)

Why do we need to probe further and how can we continue ?

(ii) The role of symmetries in physics

~~The symmetry of physical laws~~

A great common scheme for the macroscopic ~~and the~~ microscopic world

From patterns to knowledge

From symmetries to forces (gauge invariance)

(iii) Particle physics and the early Universe

Understanding the "Big Bang"

Present CERN physics $\rightarrow 10^{-10}$ sec

The present answer to the question

~~What is the~~ world made of ?

What holds it together ?

" Das Ich erkenne was die Welt
im Innersten zusammen hält " (In Faust)

A one sentence summary of the natural ~~sciences~~

" The World is made of atoms " (R. Feynman)

A vision of the world at $10^{-10}$ m $(\alpha, m)$

Structure and complexity (biology) of macroscopic objects $\frac{e^2}{\hbar c}$

At present we can probe down to $10^{-18}$ m

The Standard Model $(\sim 20)$

The beauty and power of the Standard Model lies in ~~the fact~~ that hundreds of particles and processes can be explained on the basis of a few types of quarks and leptons and their interactions

Electromagnetic , Weak and Strong interactions based on a simple mathematical structure

Symmetry $SU(3) \times SU(2) \times U(1)$

# – Part 1 –

## Particle Physics – An overview

To meditate on the union of the microscopic and the macroscopic in philosophy, to quantify their dualism in physics

T. D. Lee

It is a wonderful feeling to recognize the Unifying features of a complex of phenomena which present themselves as quite unconnected to the direct experience of the senses

A. Einstein

# Introduction to particle physics for non particle physicists

The non particle physicist

A person interested in knowing about
The purpose of CERN
Its achievements and those of
its sister-laboratories

A person who, being at CERN, has heard
about the words (quark, CP violation ....)

A person who wishes to know what
is behind them

The Unity of Physics

Physics is

Facts
Concepts  freely invented
Principles

Explicit Mathematics limited to partial derivatives

Well known results of Group theory will be
worked out whenever needed.

— Part 1 – a

Particle Physics an overview

Quantum Mechanics
Relativity

→ Feynman Graphs
Real and virtual particles

QED

Weak Interactions

The ElectroWeak Interaction
Neutral Currents
The W and Z

The quark structure of the proton
Hadronic jets

Success, Problems and Hopes
to Guts and Superstring
The $10^{-19}$ m frontier